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This report

"Lining of Waste Impoundment and Disposal Facilities" provides information on performance, selection, and installation of specific liners and cover materials for specific disposal situations, based upon the current state of the art of liner technology and other pertinent technology. It contains descriptions of wastes and their effects on linings; a full description of various natural and artificial liners; liner service life and failure mechanisms; installation problems and requirements of liner types; costs of liners and installation; and tests that are necessary for preinstallation and monitoring surveys.

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AND DISPOSAL FACILITIES

by

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Permit Writers Guidance Manual/Technical Resource Document

Preface

The land disposal of hazardous waste is subject to the requirements of Subtitle C of the Resource Conservation and Recovery Act of 1976. This Act requires that the treatment, storage, or disposal of hazardous wastes after November 19, 1980, be carried out in accordance with a permit. The one exception to this rule is that facilities in existence as of November 19, 1980 may continue operations until final administrative dispostion is made of the permit application (providing that the facility complies with the Interim Status Standards for disposers of hazardous waste in 40 CFR Part 265). Owners or operators of new facilities must apply for and receive a permit before beginning operation of such a facility.

The Interim Status Standards (40 CFR Part 265) and some of the administrative portions of the Permit Standards (40 CFR Part 264) were published by EPA in the Federal Register on May 19, 1980. EPA will soon publish technical permit standards in Part 264 for hazardous waste disposal facilities. These regulations will ensure the protection of human health and the environment by requiring evaluations of hazardous waste management facilities in terms of both site-specific factors and the nature of the waste that the facility will manage.

The permit official must review and evaluate permit applications to determine whether the proposed objectives, design, and operation of a land disposal facility will be in compliance with all applicable provisions of the regulations (40 CFR 264).

EPA is preparing two types of documents for permit officials responsible for hazardous waste landfills, surface impoundments, and land treatment facilities: Permit Writers Guidance Manuals and Technical Resource Documents. The Permit Writers Guidance Manuals provide guidance for conducting the review and evaluation of a permit application for site-specific control objectives and designs. The Technical Resource Documents support the Permit Writers Guidance Manuals in certain areas (i.e. liners, leachate management, closure, covers, water balance) by describing current technologies and methods for evaluating the performance of the applicant's design. The information and guidance presented in these manuals constitute a suggested approach for review and evaluation based on best engineering judgments. There may be alternative and equivalent methods for conducting the review and evaluation. However, if the results of these methods differ from those of the EPA method, their validity may have to be validated by the applicant.

In reviewing and evaluating the permit application, the permit official must make all decisions in a well defined and well documented manner. Once an initial decision is made to issue or deny the permit, the Subtitle C regulations (40 CFR 124.6, 124.7 and 124.8) require preparation of either a statement of basis or a fact sheet that discusses the reasons behind the decision. The statement of basis or fact sheet then becomes part of the permit review process specified in 40 CRF 124.6-124.20.

These manuals are intended to assist the permit official in arriving at a logical, well-defined, and well-documented decision. Checklists and logic flow diagrams are provided throughout the manuals to ensure that necessary factors are considered in the decision process. Technical data are presented to enable the permit official to identify proposed designs that may require more detailed analysis because of a deviation from suggested practices. The technical data are not meant to provide rigid guidelines for arriving at a decision. References are cited throughout the manuals to provide further guidance for the permit official when necessary.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report was conceived and developed with the goal of providing a comprehensive document that would be a useful tool for all interested and involved parties who are participating in pollution control and management activities. The above objectives have served as guiding principles for which this document was prepared.

The following report describes and details the major aspects of liners for hazardous waste impoundments. Various procedures are presented as to the selection, manufacture, construction, and use of the major types of liners.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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CHAPTER 1. INTRODUCTION

The use of man-made materials of low permeability to line waste storage and disposal impoundments has been demonstrated to be a feasible method of preventing leachate and waste liquid components from leaking from an impoundment and subsequently entering and polluting groundwater. These liner materials can also be used to prevent the migration of dangerous concentrations of methane and other gases from a waste containment site. A wide range of materials is available from which to choose for the containment of specific wastes.

This Manual is intended to provide information and guidance in the selection, performance, installation,and maintenance of specific liners and cover materials for specific containment situations, based upon the current state-of-the-art of liner technology and other pertinent technologies.

Chapter 2 of this document contains descriptions and characteristics of various types of wastes with reference to some of their polluting and potentially polluting components. Several selected industrial waste streams are described.

The various lining materials which are potentially useful and their associated technologies are described in Chapter 3. These linings include remolded and compacted soils and clays, admixes, polymeric membrane liners, sprayed-on liners, soil sealants, and chemisorptive liners.

The specific characteristics of liner materials in service environments with various types of wastes are discussed in Chapter 4, particularly with respect to their compatibility with wastes, their permeability to water and waste constituents, failure mechanisms, and estimated service lives. Additional waste characertization is presented for screening and selection purposes. This chapter also introduces several testing procedures for evaluating the waste/liner interaction.

The design and construction of waste facilities with the various types of lining materials are described in Chapter 5 with particular emphasis on the installation of membrane liners and the problems associated therewith. Attention is given to the specific requirements for site and surface preparation and placing of covers on membrane liners to prevent puncturing. Special problems are associated with the design and construction of solid waste disposal sites, i.e. solid waste landfills. The subject of leachate collection above the liner is discussed.

The operation, management, and maintenance of disposal facilities having different lining materials are described in Chapter 6. Particular attention is paid to the facilities that have membrane liners and groundwater monitoring. A plan for monitoring the liners is suggested. Standard operating procedures are discussed. Also included is a section on unacceptable practices.

The historical costs of installing various liner materials for different types of wastes are discussed in Chapter 7.

In Chapter 8, several parameters for selecting a specific liner or a group of satisfactory liners for a given containment facility are presented. These include the use of compatibility tests, moderate duration exposure tests, soil condition tests, prior performance in similar facilities, costs, etc.

Methods for the preparation of proper specifications for selected liners or groups of liners are suggested in Chapter 9.

At the end of each chapter of this document, a list of references from which information is taken is presented. A bibliography is also presented for those wishing to obtain additional information on specific subject topics.

In the appendixes, more detailed information is presented on specific subject areas dealing mostly with development of the actual facilities. Appendix II lists liner industry firms and organizations. A description of test methods is presented in Appendix III. There are appendixes with detailed discussions on the installation of flexible polymeric membrane liners, a leachate collection system network, swell behavior of soils and clays, optimization of soil liner design and proposed specifications for flexible polymeric membrane materials. In addition, a case study analysis methodology is presented for lined impoundments. Because of the diverse origins of liner technology and the broad spectrum of potential uses of this Manual, a glossary of terms used in this Manual is included.

This Manual does not deal with the following subjects, except by reference:

1. Site selection, except when specific liners cannot be used.

2. Detailed discussion of methods of analysis of wastes, except for information on waste components that are aggressive to linings of all types.

3. Monitoring of groundwater.

4. Attenuation of pollutants in the soil below the liner.

5. Legal aspects.

6. Final cover and closure.

This Manual attempts to bring together the current knowledge and technology related to liners and the disposal of wastes. As new technology is developed and as experience in the use of liners becomes available, this Manual will be up-graded on a chapter-by-chapter basis.

CHAPTER 2. CHARACTERISTICS OF WASTES AND WASTE FLUIDS

2.1 Introduction

From the standpoint of pollution and need for containment, it is the waste fluids with which we are primarily concerned. They carry the dissolved pollutants and have the capability of flowing and migrating out of a disposal site. A polluting species in a solid waste must first dissolve into a liquid before it can migrate through the ground. Furthermore, it is the fluid and the dissolved constituents that can be aggressive to liner materials. Water, itself, can be an aggressive constituent, causing the liner material to swell. Consequently, the discussion in this chapter of the waste and waste fluids is directed principally to the effects of wastes on liners.

The complexity of waste fluids, which include water, dissolved organic and inorganic components, organic chemicals and solvents of great variety, and bacteria, magnify the problems of containment.

The determination of the disposal requirements for wastes in lined facilities is mandated by public law and enforced through EPA and state regulations. Selected representative wastes of the following types are discussed:

- Municipal solid waste.
- Hazardous wastes from eight industries
- Other nonradioactive and special wastes.

The liner problems that are encountered with these waste streams should be typical of those that must be solved generally. Also included in this chapter is a section (2.5) concerned with the general properties of waste fluids, particularly with respect to their potential interaction with liners. A more complete discussion of the interaction of wastes and liners is given in Chapter 4.

2.2 Municipal Solid Waste

2.2.1 Description of the Waste

Municipal solid waste (MSW) is that refuse from residential and commercial sources that is usually collected from garbage cans and trash bins. Typical components of municipal refuse include paper, glass, plastics, rubber, wood, metal, food and garden wastes, ceramics, rocks, textiles, leather, etc. Major components and rough wet weight percents are presented in Table 2-1 from Ham et al. (1979). See Wigh (1979) for additional data. However, it is the leachate generated within the waste that is of concern from the standpoint of pollution and liner durability.

Table 2-1. COMPOSITION AND ANALYSIS OF AN AVERAGE MUNICIPAL REFUSE FROM STUDIES BY PURDUE UNIVERSITY[a]

Component	Percent of all refuse by weight	Moisture (percent by weight)	Analysis (percent dry weight)						
			Volatile matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Non-combus-tibles
Rubbish, 64%:									
Paper	42.0	10.2	84.6	43.4	5.8	44.3	0.3	0.20	6.0
Wood	2.4	20.0	84.9	50.5	6.0	42.4	0.2	0.05	1.0
Grass	4.0	65.0	...	43.3	6.0	41.7	2.2	0.05	6.8
Brush	1.5	40.0	...	42.5	5.9	41.2	2.0	0.05	8.3
Greens	1.5	62.0	70.3	40.3	5.6	39.0	2.0	0.05	13.0
Leaves	5.0	50.0	...	40.5	6.0	45.1	0.2	0.05	8.2
Leather	0.3	10.0	76.2	60.0	8.0	11.5	10.0	0.40	10.1
Rubber	0.6	1.2	85.0	77.7	10.4	...	...	2.0	10.0
Plastic	0.7	2.0	...	60.0	7.2	22.6	...	...	10.2
Oils, paints	0.8	0.0	...	66.9	9.7	5.2	2.0	...	16.3
Linoleum	0.1	2.1	65.8	48.1	5.3	18.7	0.1	0.40	27.4
Rags	0.6	10.0	93.6	55.0	6.6	31.2	4.6	0.13	2.5
Street sweepings	3.0	20.0	67.4	34.7	4.8	35.2	0.1	0.20	25.0
Dirt	1.0	3.2	21.2	20.6	2.6	4.0	0.5	0.01	72.3
Unclassified	0.5	4.0	...	16.6	2.5	18.4	0.05	0.05	62.5
Food wastes, 12%:									
Garbage	10.0	72.0	53.3	45.0	6.4	28.8	3.3	0.52	16.0
Fats	2.0	0.0	...	76.7	12.1	11.2	0.0	0.00	0.0
Noncombustibles, 24%:									
Metals	8.0	3.0	0.5	0.8	0.04	0.2	...	...	99.0
Glass & ceramics	6.0	2.0	0.4	0.6	0.03	0.1	...	...	99.3
Ashes	10.0	10.0	3.0	28.0	0.5	0.8	...	0.5	70.2
Composite refuse, as received:									
All refuse	100	20.7	...	28.0	3.5	22.4	0.33	0.16	24.9

[a] Ham et al., 1979.

2.2.2 Characteristics of Leachate From Municipal Solid Waste

Leachate is liquid that has extracted, dissolved, or suspended organic and inorganic materials from wastes as a result of percolation through the decomposing refuse.

The leachate produced from municipal refuse is a highly complex liquid mixture of soluble, insoluble, organic, inorganic, ionic, nonionic, and bacteriological constituents in an aqueous medium. It contains products of the degradation of organic materials and soluble ions which may present a pollution problem to surface and ground waters (Phillips and Wells, 1974). The quality of the leachate depends on the composition of the waste and the combined physical, chemical, and biological activities.

The precise composition of leachate is, of course, waste and site specific, depending on such variables as types of wastes, amount of infiltrating water, and pH. Table 2-2 lists parameters of leachate which are used as analytical indicators of landfill leachate in the groundwater near a landfill (EPA, 1977). Tables 2-3 and 2-4 present data to show the complexity in composition of actual leachate from MSW, its site specific character and its variation with time.

Griffin and Shimp (1978) compared the analyses of municipal landfill leachate with drinking water standards. COD and BOD of landfill leachates were generally high and the pH ranged from 4 to 9. Alkalinity, hardness, phosphate, nitrogen, heavy metals, and concentrations of other elements were also determined. The levels of these components varied over a very wide range (Tables 2-3 and 2-4).

Leachates generated by the disposal of hazardous wastes may include high concentrations of such heavy metals as mercury, cadmium and lead; toxic substances, such as barium and arsenic; organic compounds, including chlorinated solvents, aromatic hydrocarbons, and organic esters; and various corrosive, ignitable or infectious materials.

2.2.3 Gas Production in MSW

Gases are also produced in the decomposition of organic matter in MSW landfills. These gases, primarily methane and carbon dioxide, may present problems if their migration is not controlled or if they are not collected. Methane is flammable, can be explosive, is damaging to plants and trees, and, in high enough concentration, may result in asphyxiation of animals and people. Methane is of commercial value as a heating fuel and is being used in this manner. Carbon dioxide is absorbed in leachate and tends to lower its pH and thus to solubilize calcium, magnesium, iron, and other metals.

2.2.4 Potential Pollution Effects of MSW Leachate

Municipal landfill leachates degrade groundwater quality by introducing the constituents shown in Tables 2-3 and 2-4 as well as biological contamination (Phillips and Wells, 1974).

TABLE 2-2. LEACHATE PARAMETERS[a]

Physical	Chemical		Biological
	Organic	Inorganic	
Appearance	Phenols	Total bicarbonate	Biochemical oxygen demand (BOD)
pH	Chemical oxygen demand (COD)	Solids (TSS, TDS)	Coliform bacteria (total, fecal; fecal streptococcus)
Oxidation-reduction potential	Total organic carbon (TOC)	Volatile solids	Standard plate count
Conductivity	Volatile acids	Chloride	
Color	Tannins, lignins	Phosphate	
Turbidity	Organic-N	Alkalinity and acidity	
Temperature	Ether soluble (oil and grease)	Nitrate-N	
Odor	MBAS	Nitrite-N	
	Organic functional groups as required	Ammonia-N	
	Chlorinated hydrocarbons	Sodium	
		Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Hg, As, Se, Ba, Ag)	
		Cyanide	
		Fluoride	

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[a] EPA, 1977.

TABLE 2-3. COMPOSITION OF THREE MSW LANDFILL LEACHATES
Concentration of Constituents (mg/L)

	Source of data		
Constituent	Wigh, 1979	Breland, 1972	Griffin and Shimp, 1978
BOD_5	...	13,400	...
COD	42,000	18,100	1,340
TOC	...	5,000	...
Total solids	36,250	12,500	...
Volatile suspended solids	...	76	...
Total suspended solids	...	85	...
Total volatile acids as acetic acid	...	9,300	333
Acetic acid	...	5,160	...
Propionic acid	...	2,840	...
Butyric acid	...	1,830	...
Valeric acid	...	1,000	...
Organic nitrogen as N	...	107	...
Ammonia nitrogen as N	950	117	862
Kjeldahl nitrogen as N	1,240	...	...
pH	6.2	5.1	6.9
Electrical conductivity (μmho/cm)	16,000	...	...
Total alkalinity as $CaCO_3$	8,965	2,480	...
Total acidity as $CaCO_3$	5,060	3,460	...
Total hardness as $CaCO_3$	6,700	5,555	...
Chemicals and metals:			
Arsenic	...	...	0.11
Boron	...	...	29.9
Cadmium	...	...	1.95
Calcium	2,300	1,250	354.1
Chloride	2,260	180	1.95
Chromium	...	...	<0.1
Copper	...	...	<0.1
Iron	1,185	185	4.2
Lead	...	...	4.46
Magnesium	410	260	233
Manganese	58	18	0.04
Mercury	...	...	0.008
Nickel	...	...	0.3
Phosphate	82	1.3	...
Potassium	1,890	500	...
Silica	...	...	14.9
Sodium	1,375	160	748
Sulfate	1,280	...	<0.01
Zinc	67	...	18.8

TABLE 2-4. CHARACTERISTICS OF MSW LEACHATES[a]

Constituent	Range[b] (mg/L)	Range[c] (mg/L)	Range[d] (mg/L)	Range[e] (mg/L)	Leachate[f] Fresh	Leachate[f] Old
BOD_5	9-54,610	...	7,500-10,000	...	14,950	...
COD	0-89,520	100-51,000	16,000-22,000	500-1,000	22,650	81
Total dissolved solids	0-42,276	...	10,000-14,000	...	12,620	1,144
Total suspended solids	6-2,685	...	100-700	...	327	266
Total nitrogen	0-1,416	20-500	...	...	989	7.51
pH	3.7-8.5	4.0-8.5	5.2-6.4	6.3-7.0	5.2	7.3
Electrical conduc- µmho/cm)	...	...	6,000-9,000	1,200-3,700	9,200	1,400
Total alkalinity as $CaCO_3$	0-20,850	...	800-4,000	630-1,730	...	...
Total hardness as $CaCO_3$	0-20,800	200-5,250	3,500-5,000	390-800	...	...
Chemicals and Metals:						
Cadimum (Cd)	...	...	0.4	...	...	...
Calcium (Ca)	5-4,080	...	900-1,700	111-245	2,136	254
Chloride (Cl)	34-2,800	100-2,400	600-800	100-400	742	197
Copper (Cu)	0-9.9	...	0.5	<0.04-0.11	0.5	0.1
Iron (Fe)	0.2-5,500	200-1,700	210-325	20-60	500	1.5
Lead (Pb)	0-5.0	...	1.6	...	...	...
Magnesium (Mg)	16.5-15,600	...	160-250	22-62	277	81
Manganese (Mn)	0.6-1,400	...	75-125	1.02-1.25	49	...
Phosphate (P)	0-154	5-130	...	21-46	7.35	4.96
Potassium (K)	2.8-3,770	...	295-310	107-242	...	...
Sodium (Na)	0-7,700	100-3,800	450-500	106-357	...	...
Sulfate (SO_4)	1-1,826	25-500	400-650	13-84	...	...
Zinc (Zn)	0-1,000	1-135	10-30	<0.04-0.47	45	0.16

[a] EPA-OSWMP, 1975. [b] EPA-OSWMP, 1973. [c] Steiner et al., 1971. [d] Genetelli and Cirello, 1976.
[e] Ham, 1975. [f] Brunner and Carnes, 1974.

The quantity of leachate produced is a function of the moisture content of the waste itself and the volume of water added through infiltration and percolation from surface and ground sources. Leachate is being recycled in some installations to enhance biodegradation in the landfill by providing nutrients and water, thus reducing the quantity or quality of leachate produced and the pollution potential.

2.2.5 Potential Effects of MSW Leachate Upon Liners

The MSW leachate is not inert toward lining materials; constituents of the leachate can affect liners in different ways, depending on their concentrations in the leachate and on the specific liner materials. Furthermore, the effects of the constituents can be synergistic and can vary with time as the concentrations change with the aging of the waste. Dissolved salts and ions may be damaging to some lining materials, particularly soils and clays. Acidity or alkalinity may dissolve components of soils or soil cements. Organic molecules (indicated by volatile acid content, volatile solid, and COD) can be damaging to rubber and plastic liners causing them to swell, to become more permeable and softer, thus to be more easily torn and damaged. Water can cause some liners to swell, etc. These effects are discussed in detail in Chapter 4. Also discussed in Chapter 4 is the need for compatibility testing when the waste fluid or leachate is known to contain constituents that are particularly aggressive to some types of liner materials.

2.3 Hazardous Wastes

2.3.1 Introduction

Hazardous wastes disposed in land disposal facilities fall into four physical classes:

1. Aqueous-inorganic
2. Aqueous-organic
3. Organic
4. Sludges, slurries, and solids (EPA-OSWMP, 1974)

Cheremisonoff et al. (1979) estimated that 90% (by weight) of industrial hazardous wastes are produced as liquids. These liquids are further estimated to be 40% inorganic and 60% organic (EPA-OSWMP, 1974).

Aqueous-inorganic is the class of wastes in which water is the solvent (dominant fluid) and the solutes are mostly inorganic. Examples of these solutes are inorganic salts, metals dissolved in inorganic acids, and basic materials like caustic soda. Examples of wastes fitting in this category are brines, electroplating waste, metal etching wastes, caustic rinse solutions, and spent metal catalysts.

Aqueous-organic is the class of wastes in which water is the solvent and the solutes are predominantly organic. Examples of these solutes are organic chemicals that are polar or charged as is inferred by their water-solubility.

Examples of this class of waste are wood preserving wastes, water base dye wastes, pesticide container rinse water, and ethylene glycol production wastes.

Organic is that class of wastes in which an organic fluid is the solvent or dominant fluid and the solutes are the other organic chemicals dissolved in the organic solvent. Examples of this class of wastes are oil base paint waste, pesticide manufacturing wastes, spent motor oil, and spent cleaning solvents.

Sludges represent the fourth class of wastes. They are generated when a waste stream is dewatered, filtered, or treated for solvent recovery. Sludges are characterized by a high solids content such as found in settled matter or filter cakes and consists largely of clay minerals, silt, precipitates, fine solids, and high molecular weight hydrocarbons. Examples of this waste are American Petroleum Institute (API) separator sludge, storage tank bottoms, treatment plant sludge or any filterable solid from any production or pollution control process.

Both economic and pollution control pressures continue to mandate solvent recovery and reductions in discharges from aqueous waste streams. These factors have and will continue to make sludges the fastest growing class of wastes. After placement of sludges in a waste disposal facility, leachates migrate out of the sludge due to gravitational forces, overburden pressures and hydraulic gradients. These leachates are similar in physical form to the first three classes of waste discussed.

Industrial wastes are a major source of hazardous waste, the components of which are usually heavy metals, strong acids or bases, and a large array of organic and inorganic chemicals. As shown in Table 2-5, taken from the EPA Report to Congress on the disposal of hazardous wastes (EPA-OSWMP, 1974), each industry produces wastes with different characteristics and components. Also, wastes frequently vary with the source in the same industry. The chemical nature and reactivity as well as concentration of the waste components must be considered when choosing a liner for a given impoundment. The characteristics of the wastes from several selected industries are discussed below, as examples of specific wastes which may be encountered.

2.3.2 Pesticide Industry (SIC 287)

The diverse nature of the pesticide industry and its marketing strategy makes it difficult to analyze and assess the impact of specific active ingredients and their finished formulations. For example, there were some 24,000 different formulations available from 139 manufacturers and 5,660 formulators as of February 1976. Over 50,000 different products are said to have been registered by the EPA. Each company that markets a given formulation of finished pesticide must have a registered label for it. Over 3,500 companies hold federal registrations for one or more products. In addition, many pesticides are registered for intrastate sale only; an estimated 2,000 pesticidal products are registered in California alone (Wilkinson, 1978).

TABLE 2-5. REPRESENTATIVE HAZARDOUS SUBSTANCES WITHIN INDUSTRIAL WASTE STREAMS

Industry	Hazardous substances										
	Arsenic	Cadmium	Chlorinated hydrocarbons[a]	Chromium	Copper	Cyanides	Lead	Mercury	Misc. organics[b]	Selenium	Zinc
Battery		X		X	X						X
Chemical manufacturing			X	X	X			X	X		
Electrical and electronic			X		X	X	X	X		X	
Electroplating and metal finishing		X		X	X	X					X
Explosives	X				X		X	X	X		
Leather				X					X		
Mining and metallurgy	X	X		X	X	X	X	X		X	X
Paint and dye		X		X	X	X	X	X	X	X	
Pesticide	X		X			X	X	X	X		X
Petroleum and coal	X		X				X				
Pharmaceutical	X							X	X		
Printing and duplicating	X			X	X		X		X	X	
Pulp and paper								X	X		
Textile				X	X				X		

[a] Including polychlorinated biphenyls.

[b] For example: acrolein, chloropicrin, dimethyl sulfate, dinitrobenzene, dinitrophenol, nitroaniline, and pentachlorophenol.

Many pesticide and general biocide production wastes are aqueous solutions or suspensions of organic and halogenated organic compounds. Some biocide wastes are those from the production of: Dieldrin, Methylparathion, Dioxin, Aldrin, Chlordane, DDD, DDT, 2,4-D, Endrin, Guthion, Heptachlor, and Lindane. Inorganic based wastes result from the production of arsenic, arsenate, and mercurial compounds. Thallium and thallium sulfate are found in rodenticide wastes (EPA-OSWMP, 1974).

Pesticide wastes result largely from the periodic cleaning of formulation lines, filling equipment, spills, area washdown, drum washing, air pollution control devices, and area runoff. Wash waters and steam condensates from cleaning operations are the sources of liquid waste from the formulation lines and filling equipment. Steam cleaning condensates and rinse waters from other processing units such as the mix tanks, drum washers, and air pollution control equipment are also sources of pesticide waste. The scrubber waters themselves are a waste stream with area washdown, leaks, and spills making up the remaining principal sources.

The principal constituents of wastewaters from the pesticide industry are dissolved organics, suspended solids, dissolved inorganic solids, and variable pH. As stated above, the great variety of manufactured end products effectively precludes the presentation of a "general" waste composition chart or table.

Because of the great range of sizes of pesticide manufacturing plants, it is plausible to expect the following developments to occur with respect to the disposal of generated wastes. For the small generator, the produced waste, due to small total volume and small relative volume, might be accepted into a municipal wastewater management system. In such an instance, the pollution impact, if discernible, would be minor. For the large generator, the facility would probably have its own wastewater pretreatment or treatment system, in which case, the waste would most likely be partially treated, then concentrated. The concentrated waste would be hauled to a landfill for disposal or containerized and hauled to a landfill.

Concentrations of individual wastewater contaminants are frequently not reported but the waste stream in general is characterized by COD, BOD_5, TSS, TDS, and TOC (Becker, 1975).

2.3.3 Soap and Detergent Industry (SIC 2841)

Another less dangerous, class of organic wastes are those from the soap and detergent industries. Soap manufacturing produces a waste high in fatty acids, lye, zinc, alkali earth salts, and caustic soda which are used as catalysts and in neutralization. Glycerine is formed as a by-product of soap production but much of this is recovered and recycled. Sulfuric acid and sulfonic acid are used in the preparation of some soaps; the pH of the wastes generated in these processes is very low. Soap production wastes also include alcohols and alkylbenzenes. The waste stream is generally high in COD, BOD5, TDS, acidity, oil and grease (Gregg, 1974). The EPA publication on soap and detergent manufacturing (Gregg, 1974) is a good source of additional information on the manufacturing processes, waste constituents, and waste disposal techniques for this industry.

Soap and detergent industry waste is emphasized here due to the potential synergistic effects it may have upon a liner by creating a broader dispersion of pollutants from mixing.

2.3.4 Paint Industry (SIC 285)

The paint and allied products industries utilize many organic and inorganic raw materials, some of which are present in the wastes. There is no waste stream in the sense of wastes as by-products of production. The wastes come mainly from the packaging of raw materials, air and water pollution control equipment, off-grade products and spill, most of which is reclaimed and reused except for paint absorbed onto final clean-up material. Coatings containing significant amounts of toxic metals are reworked and wastes contain little or no metallic residues. Most spoiled batches are incorporated in later batches whenever possible and spills are salvaged.

In the preparation of paint and coatings, a number of metal compounds are used as pigments; oils and polymer resins are used as bases and solvents are used as thinners. These ingredients become part of the waste as spoiled batches or spills. This waste constitutes about 0.2% of production. Toxic chemical usage is strictly limited so a proportionally small amount of toxic substances (mainly mercury and lead) reach the waste stream from this source. Waste wash solvents generally have higher boiling points and similar solvency to those used in the paint. Waste wash solvent is retained and reused in later batches or is reclaimed by distillation or sedimentation on site. It may be sent to an outside contractor for processing. The solvent is then returned to the plant for reuse.

Equipment used for water-thinned paints is cleaned with water and sometimes detergent. The wash water is settled, used as a thinner for later batches of the same type of paint or, where acceptable, released to the muncipal sewer system. Wash water from very dark colors, experimental or spoiled batches is usually placed in drums and disposed into a landfill.

The potentially hazardous materials in paints include: inorganic metals such as arsenic, beryllium, cadmium, chromium, copper, cobalt, lead, mercury, selenium, asbestos, cyanides, and organic compounds such as halogenated hydrocarbons, and organic pesticides (WAPORA, Inc., 1975).

Of the total estimated waste stream of 389,000 metric tons generated by the paint and coatings industry, 24.6% is potentially hazardous, 3.6% is hazardous solvents, and 0.2% is toxic chemical compounds (Figure 2-1). Figure 2-2 gives the quantities of various components in the toxic waste stream. A detailed list of waste components and quantities is available in the reference by WAPORA, Inc. (1975).

2.3.5 Inorganic Chemicals Industry (SIC 281)

The waste streams of a few of the specific industries in this category are briefly described in this section.

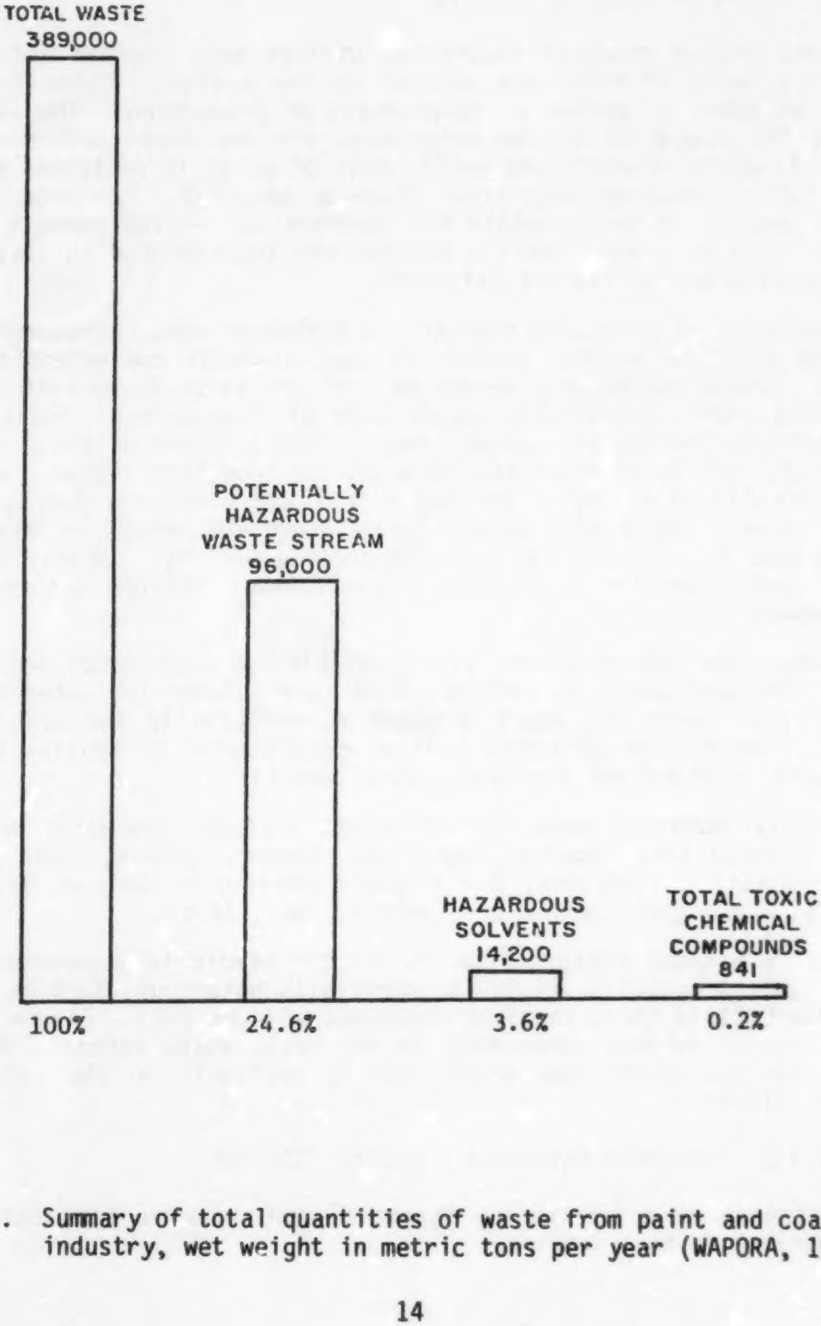

Figure 2-1. Summary of total quantities of waste from paint and coatings industry, wet weight in metric tons per year (WAPORA, 1975).

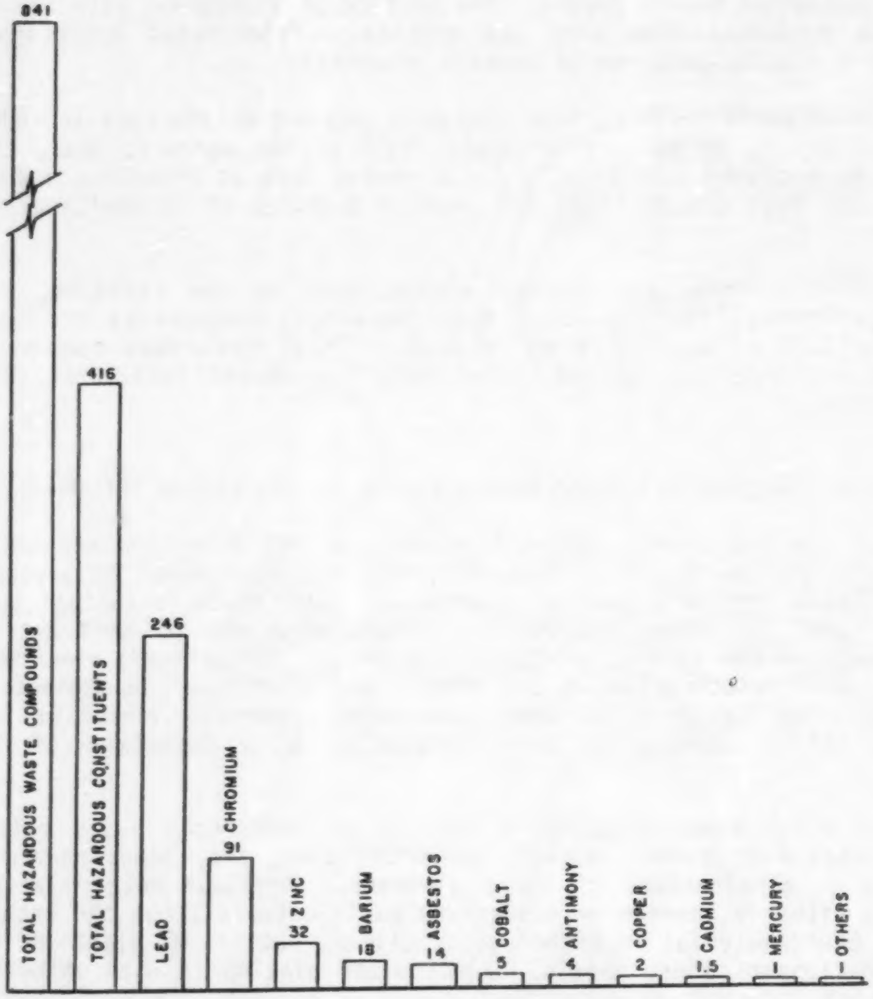

Figure 2-2. Toxic chemical compounds in waste generated by the paint industry, wet weight in metric tons per year (WAPORA, 1975).

The chlor-alkali industry, whose main product is chlorine, also produces soda ash (NaOH) or potash (KOH) as co-products. Brine-purification sludges resulting from this industry contain mainly calcium carbonate, magnesium hydroxide, barium sulfate, and water. These slightly hazardous or non-hazardous wastes do not necessarily require strict landfilling precautions or procedures. Lead carbonate and asbestos waste products must be handled more carefully. Lead must be completely isolated from the environment before land disposal. Asbestos is insoluble, but the dust and small fibers present a serious potential health hazard. The surface of a disposal site for asbestos should be protected from wind and erosion. Chlorinated hydrocarbons and mercury are also by-products of certain processes.

The hazardous waste products from inorganic pigment manufacture include chrome and small amounts of mercury or lead. Most of the mercury, lead, zinc, and antimony is reclaimed. Minimally toxic wastes such as chlorides and nontoxic metal oxides from ore residues are usually disposed of in municipal sanitary landfills.

Other inorganic chemicals produce wastes such as ore residues, silicates or easily neutralized liquids. Most hazardous components are reclaimed or become part of a salable by-product. Those hazardous components not reclaimed are usually disposed of in lined impoundment facilities (Hallowell et al., 1976).

2.3.6 Electroplating and Metals Finishing Industries (SIC 3471)

Because of the heavy metal wastes from the electroplating and metal finishing operations, all wastes from this industry are considered hazardous. The electroplating industry can be classified into three principal segments: plating, metal finishing, and the manufacture of printed circuit boards. The plating segment can be further subdivided into: common metal electroplating, precious metal electroplating and electroless plating. Subsegments of the metal finishing category include: anodizing, chemical conversion coating, chemical milling, etching and immersion plating (U. S. Department of Interior, 1980).

In common metal electroplating, a ferrous or nonferrous basis material is electroplated with copper, nickel, chromium, zinc, tin, lead, cadmium, iron, aluminum, or combinations of these elements. Precious metal electroplaing also uses either a ferrous or nonferrous basis material, but the metal plated onto the basis material is either gold, silver, palladium, platinum, rhodium, or combinations of these metals. Electroless plating is used on both metals and plastics.

Anodizing, coatings (e.g. chromating or phosphating), coloring, and immersion plating processes apply a surface coating to a workpiece for specific functional or decorative purposes. Chemical milling and etching processes are used to produce specific design configurations and tolerances on metal parts by controlled dissolution with chemical reagents or etchants.

Wastewaters from plating and metal finishing operations are discharged from all three phases of the electroplating process: 1) workpiece pretreatment; 2) the plating, coating, or basis material removal process; 3) post treatment. Wastewaters are generated by rinse water disposal, plating, or finishing bath dumping, ion exchange (IE) unit regenerant bleed streams, vent scrubber discharges, and maintenance discharges (U. S. Department of Interior, 1980).

Treatment may involve degreasing with soaps, alkaline cleaning (sometimes with the aid of wetting agents), acid dipping, or, in the case of aluminum alloys, desmutting to remove finely divided particles of base material. The compositions of treatment cleaners (and thus, waste streams) vary with the type of base metal being cleaned and the kind of material being removed.

Wastewater constituents generated from the electroplating depend on the metals being plated and the plating solution used. Table 2-6 lists some of the various types of plating solutions used for electroplating. Plating solutions for the metals in the platinum group are proprietary. The most common plating solutions for electroless plating are copper and nickel, although iron, cobalt, gold, palladium, and arsenic are also used. Of particular concern among the constituents of electroless plating baths are the chelating agents, which are used to hold the metal in solution (so the metal will not plate out indiscriminately). There are three main types of chelating agents: amino carboxylic acids, amines, and hydroxy acids. One of the drawbacks in the use of chelating agents is the difficulty in precipitating chelated metals out of wastewater during treatment.

Wastes from metal finishing operations comes from cleaning, pickling, anodizing, coating, etching, and related operations. The constituents in this waste include the basis material being finished, as well as the components in the processing solutions. Baths used for anodizing, coating, and etching usually contain metal salts, acids, bases, dissolved basis metals, complexing agents, and other deposition control agents. Bath constituents for chemical removal of basis metals include mineral acids, acid chlorides, alkaline ammonium solutions, nitro-organic compounds, and such compounds as ammonium peroxysulfate.

Post treatment processes in the plating segment encompass chemical conversion coatings (chromating, phosphating, and coloring), which are process steps for the metal finishing segment. Post treatment processes for metal finishing include: sealing and coloring of anodic coatings, bleaching or dyeing of chromate coatings, and chemical rinsing after phosphating.

Table 2-7 is a compilation of the various pollutants found in each subsegment of the industry. The concentrations presented are the range of values for each constituent, based on a statistical analysis of 50 metal finishing plants and 67 plating establishments (U.S. Department of Interior, 1980).

Hallowell et. al (1976) identified four waste streams as being destined for land disposal. They include water pollution control sludges, process wastes, degreasing sludges and the salt precipitates from electroless nickel bath regeneration. Hallowell et al. have estimated the quantities of these which

TABLE 2-6. TYPICAL PLATING SOLUTIONS[a]

Basis material	Plating Solution
Copper	Plain cyanide Rochelle cyanide Copper sulfate Copper fluoborate
Nickel	Sulfamate Fluoborate Chloride
Cadmium	Cyanide Fluoborate
Tin	Sulfate Fluoborate Halide
Gold	Cyanide Acid
Iron	Chloride Sulfate/chloride Fluoborate
Chromium	Chromic/sulfuric acid
Zinc	Cyanide Pyrophosphate
Lead	Fluoborate

[a] U. S. Department of Interior, 1980.

TABLE 2-7. CHARACTERIZATION OF WASTE STREAM FROM ELECTROPLATING INDUSTRY[a]

Pollutant parameter	Subpart - Concentrations (mg/L)					
	Common metals plating	Precious metals plating	Electroless plating	Anodizing	Coatings	Chemical milling and etching
Copper	0.032-272.5		0.002-47.90			0.206-272.5
Nickel	0.019-2,954		0.028-46.80			
Chromium, total	0.088-525.9			0.268-79.20	0.190-79.20	0.088-525.9
Chromium, hexavalent	0.0005-534.5			0.005-5.000	0.005-5.000	0.005-334.5
Zinc	0.112-252.0				0.138-200.0	0.112-200.0
Cyanide, total	0.005-150.0	0.005-9.970	0.005-12.00	0.005-78.00	0.005-126.0	0.005-126.0
Cyanide, amenable	0.003-130.0	0.003-8.420	0.005-1.00	0.004-67.56	0.004-67.56	0.005-101.3
Fluoride	0.022-141.7		0.110-18.00			0.022-141.7
Cadmium	0.007-21.60					
Lead	0.663-25.39					
Iron	0.410-1,482				0.410-168.0	0.075-263.0
Tin	0.060-103.4				0.102-6.569	0.068-103.4
Phosphorus	0.020-144.0	0.020-144.0	0.030-109.0	0.176-33.0	0.060-53.30	0.060-144.0
Total suspended solids	0-10,000	0-10,000	0-40	36-924.0	20-5,300	0-4,300
Silver		0.050-176.4				
Gold		0.013-24.89				
Palladium		0.038-2.207				
Platinum		0.112-6.457				
Rhodium[b]		0.034				

[a] U. S. Department of Interior, 1980.

[b] Only 1 plant had a measurable level of this pollutant.

could be generated in 1975, 1977, and 1983. These data are presented in Table 2-8.

TABLE 2-8. HAZARDOUS WASTES DESTINED FOR LAND DISPOSAL FROM THE ELECTROPLATING AND METALS FINISHING INDUSTRY (JOB SHOPS) - DATA IN METRIC TONS ON A DRY BASIS

Type of waste	1975	1977	1983
Water pollution control sludges[a]	19,740	56,399	73,882
Process wastes	42,141	42,141	55,206
Degreaser sludges	5,434	5,434	7,118
Electroless nickel wastes	11,422	11,422	15,063
Total	78,737	115,396	151,269

[a] From Hallowell et al., 1976.

[b] Total hazardous constituents in water pollution control sludges: 1975, 8,016; 1977, 22,913; 1983, 29,903.

The data in the table include only estimates for the job shops. The captive shops of this industry, which are parts of larger manufacturing companies, would make the total amount of wastes for this industry considerably larger.

The principal hazardous constituents in these wastes are the heavy metals and residual organic material. From the standpoint of the effects upon the liners, the heavy metal ions and the other inorganic constituents can be expected to affect particularly the soil type liner materials, and the residual organics that are in these wastes, including polychlorinated materials, could affect a variety of the membrane and organic type liner materials.

2.3.7 Petroleum Refining Industry

The petroleum refining industries produce very different waste streams from the various refining processes. Highly caustic sludges result from operations including washing, sweetening, and neutralizing. Spent caustic solutions are discharged from alkylation, isomerization units, and LPG treating processes. The waste stream is roughly 3-3.5% NaOH by weight. Oily refinery sludges contain sand, silt, heavy metals, and an array of organic compounds in addition to oil and water. The oil content of such wastes ranges from 1-82% by weight. Refer to Table 2-9 for concentrations and quantities of several wastes resulting from refining processes.

TABLE 2-9. RANGES OF CONCENTRATIONS AND TOTAL QUANTITIES FOR REFINERY SOLID WASTE SOURCES[a]
(All values in milligram per kilogram except where noted)

Parameters	Sludge from Clarified Once Through Cooling Water	Exchange Bundle Clearing Sludge	Slop Oil Emulsion Solids	Cooling Tower Sludge	API/Primary Clarifier-Separator Bottom	Dissolved Air Flotation Float	Kerosene Filter Clays	Lube Oil Filter Clays	Waste Biosludge
Phenols	0.0-2.1	8-18.5	5.7-68	0.6-7.0	3.8-156.7	3.0-210	2.0-25.2	0.05-6.4	1.7-10.2
Cyanide	0.01-0.74	0.0004-3.3	0-4.6	0-14	0-43.8	0.01-1.1	Trace	0.01-0.22	0-19.5
Selenium (Se)	0.1-1.7	2.4-52	0.1-6.7	0-2.4	0-7.6	0.1-4.2	0.01-26.1	0.1-2.1	0.01-5.4
Arsenic (As)	0.1-18	10.2-11	2.5-23.5	0.7-21	0.1-32	0.1-10.5	0.09-14	0.05-1.4	1.0-0.6
Mercury (Hg)	0.42-1.34	0.14-3.6	0-12.2	0-0.1	0.04-7.2	0.07-0.89	0-0.05	0.04-0.33	0-1.28
Beryllium (Be)	0.013-0.63	0.05-0.34	0-0.5	Trace	0-0.43	0-0.25	0.025-0.35	0.025-0.5	Trace
Vanadium (V)	15-57	0.7-50	0.12-75	0.12-42	0.5-48.5	0.05-0.1	13.2-42	0.5-65	0.12-5
Chromium (Cr)	16.6-103	310-311	0.1-1325	181-1750	0.1-6790	2.8-260	0.9-25.8	1.3-45	0.05-475
Cobalt (Co)	5.5-11.2	0.2-30	0.1-82.5	0.38-7	0.1-26.2	0.13-85.2	0.4-2.3	1.3-5	0.05-1.4
Nickel (Ni)	20.5-39	61-170	2.5-288	0.25-50	0.25-150.4	0.025-15	0.025-15	0.25-22	0.013-11.3
Copper (Cu)	56-180	67-75	8.5-111.5	49-363	2.5-550	0.05-21.3	0.4-12,328	0.5-8.0	1.5-11.5
Zinc (Zn)	93-233	91-297	60-656	118-1,100	25-6,596	10-1,825	6.6-35	0.5-115	3.3-225
Silver (Ag)	0.84-1.3	Trace	0-20.1	0.01-1.6	0.05-3	0-2.8	0.02-0.7	0.013-1.0	0.1-0.5
Cadmium (Cd)	0-1.0	1.0-1.5	0.025-0.19	0.06-0.6	0.024-2.0	0-0.5	0.19-0.4	0.025-1.5	0.16-0.54
Lead (Pb)	17.2-138	0.5-155	0.25-380	1.2-89	0.25-83	2.3-1,320	4.25-12	0.25-2.3	1.2-17
Molybdenum (Mo)	0.5-33	1.0-12	0.25-30	0.25-2.5	0.25-60	0.025-2.5	0.012-8.8	0.025-0.05	0.25-2.5
Ammonium Salts (as NH_4^+)	0.01-13	5-11	0-44	0.07-14	0.05-24	8.7-52	~0.01	2-4	28-30
Benz-a-pyrene	0-1.8	0.7-3.6	0-0.01	0-0.8	0-3.2	0-1.75	1.7-1.8	0.02-0.2	Trace
Oil (wt.%)	0.24-17.0	8-13	23-62	0.07-4.0	3.0-51.3	2.4-16.9	0.7-5.6	~3.9	0.01-0.53
Total Weight Metric Tons/yr.	9.7-18.0	0.4-1.0	1.4-29.2	0.1-0.13	0.3-45	13.6-31.0	0.79-127	102-682	1.8-38.5

continued -

TABLE 2-9 (continued)

Parameters	Coke Fines	Silt from Storm Water Run off	Leaded Tank Bottoms	Non-Leaded Product Tank Bottoms	Neutralized HF Alkylation Sludge (CaF_2)	Crude Tank Bottoms	Spent Line from Boiler Feedwater Treatment	Fluid Catalytic Cracker Catalyst Fines
Phenols	0.4-2.7	6.3-13.3	2.1-250	1.7-1.8	3.2-15.4	6.1-37.8	0.05-3.6	0.3-10.5
Cyanide	Trace	0.48-0.95	Trace	0-14.7	0.21-4.6	0.01-0.04	0-1.28	0.01-1.44
Selenium (Se)	0.01-1.6	1.1-2.2	0.1-3.1	1.5-22.4	0.1-1.7	5.8-53	0.01-9.2	0.01-1.4
Arsenic (As)	0.2-10.8	1.0-10	63-455	Trace	0.05-4.5	5.8-53	0.05-2.3	0.05-4.0
Mercury (Hg)	0-0.2	0.23-0.36	0.11-0.94	0.41-0.04	0.05-0.09	0.07-1.53	0-0.5	0-0.16
Beryllium (Be)	0-0.2	Trace	Trace	0.025-0.49	0.012-0.13	Trace	Trace	0.025-1.[illegible]
Vandium (V)	400-3,500	25-112	1.0-9.8	9.1-34.6	0.25-5	0.5-62	0-31.6	74.4-1,[illegible]24
Chromium (Cr)	0.02-7.5	32.5-644	9.0-13.7	12.7-13.1	0.75-5	1.9-75	0.025-27.9	12.3-19[illegible]
Cobalt (Co)	0.2-9.2	11.0-11.3	26.5-71	5.9-8.2	0.-3-0.7	3.8-37	0-1.3	0.25-37
Nickel (Ni)	350-2,200	30-129	235-392	12.4-41	7.4-103	12.8-125	0.13-26.2	47.5-950
Copper (Cu)	3.5-5.0	14.8-41.8	110-172	6.2-164	2.5-26	18.5-194	0.22-63.2	4.1-336
Zinc (Zn)	0.2-20	60-396	1190-17,000	29.7-541	7.5-8.6	22.8-425	2.0-70	19-170
Silver (Ag)	0.01-3.0	0.4-0.6	0.05-1.7	0.5-0.7	0.12-0.25	0.03-1.3	0.05-0.7	0.5-2.0
Cadmium (Cd)	0.015-2	0.1-0.4	4.5-8.1	0.25-0.4	0.012-0.12	0.025-0.42	0-1.3	0-0.5
Lead (Pb)	0.5-29	20.5-86	158-1,100	12.1-37.3	4.5-9.6	10.9-258	0.01-7.3	10-274
Molybdenum (Mo)	0.1-2.5	6.3-7.5	0.5-118	0.25-18.2	Trace	0.025-95	0-0.05	0.5-71[illegible]
Ammonium Salts (as NH_4^+)	No value	1.0	No value	0.2	Trace	2.0	Trace	No value
Benz-a-pyrene	Trace	0.03-2.5	0.02-0.4	0.3-0.9	No value	0-0.6	Trace	0-1.0
Oil (wt.%)	0-1.3	2.2-5.5	18.9-21	45.1-83.2	6.7-7.1	21-83.6	0.04-0.5	0.01-0.8
Total Weight Metric Tons	0.06-4.2	2.7	0.2-1.3	34.7-77	28-67	0.14-0.26	28.5-214.7	0.65-23.6

[a] From Stewart, 1978.

The oils, organics, high pH, and high ion concentrations may all be harmful to landfill or disposal site liners. Compatibility studies should be made before installing liners for this class of waste (Landreth, 1978).

2.3.8 Rubber and Plastics Industry

The rubber and plastics industry includes the production and manufacture of several types of natural and synthetic polymers. The properties and constituents of environmental concern in the process waste streams are:

pH
Color
Turbidity
Alkalinity
Temperature
Nitrogenous compounds
 (organic, amines, and nitrates)
Oils and greases
Dissolved solids
 (principally inorganic chemicals)
Phosphates
Phenolic compounds
Sulfides
Cyanides
Fluorides
Mercury

Chromium
Copper
Lead
Zinc
Iron
Cobalt
Cadmium
Manganese
Aluminum
Magnesium
Molybdenum
Nickel
Vanadium
Antimony
Numerous organic
 chemicals

The major pollutants in the wastewater from the rubber products industry are oil, grease, suspended solids, and extreme pH. The synthetic rubber industry has a wastewater of high COD and BOD contents; heavy metals, cyanides, and phenols are usually present in less than 0.1 mg/L concentrations (Riley, 1974). The oils, organics, and metal ions are all potentially damaging to various lining materials (Landreth, 1978).

2.3.9 Pharmaceutical Industry

Wastes generated by the pharmaceutical industry include chemically and biologically derived components. Many biological wastes may be treated by standard wastewater treatment methods, others are incinerated or landfilled. Wastes containing heavy metals, Cr, Zn, Hg, etc., are produced in limited quantities. The metals are recovered from these wastes and the residues are landfilled under carefully controlled conditions. Solvents are recycled or incinerated. Nonhazardous solid wastes are usually landfilled. This contains biological sludge from wastewater treatment, aluminum hydroxide, magnesium, and sodium salts (McMahan et al., 1975).

The major waste producing processes are extraction and concentration, product-by-product, and equipment washings. See Table 2-10 for raw waste sources and constituents. Biological wastes result from the production of vaccines, serums and other products derived or extracted from plant and animal sources. Fermentation and chemical synthesis wastes resulting from this industry frequently are a mixture of aqueous, organic, and inorganic constituents.

TABLE 2-10. RAW WASTE CONSTITUENTS FROM THE PHARMACEUTICAL INDUSTRY[a]
(g/kg Production)

	TDS	NO_3-N	Total P	Oil and grease	Cl	SO_4	Sulfide	Total Hard- ness	Ca	Mg	Cu	Phenol
Fermentation	5.990	4.68	22.0	413	1.260	274	(b)	294	123	30	0.005	0.15
Biological products and nautral extractive manfacturing	895	0.02	7.3	3.62	211	277	(b)	...	36.4	...	0.12	0.073
Chemical synthesis	1.060	0.20	7.83	21.6	104	203	...	61.6	15.2	5.68	0.002	0.16
Formulation	11.3	0.053	0.15	0.78	2.51	0.52	0.007	5.82	1.01	...	0.001	...
Research	1.33	Trace	0.23	(b)	0.94	1.27	(b)	...	...	...	...	...

[a] Riley, 1974.

[b] Data not reported.

Thus, waste-liner compatibility studies are essential before lining a disposal site for this complex type of waste.

2.4 Other Nonradioactive and Special Wastes

Wastes from power plants are usually ashes, air-pollution control equipment sludges, cooling tower blowdown and boiler and metal cleaning wastes. The wastes tend to have extreme pH's and contain large amounts of calcium sulfate, sulfites, carbonates, and metals. Metals are usually at trace levels, but the allowed limits for domestic water supplies are often exceeded by some metals (Styron and Fry, 1979). Table 2-11 presents the metal contents of several wastes. While the toxicity of this waste is relatively low, the tremendous quantities of ash and sludges produced present a major solid waste disposal problem. Fly ash has been used for a number of years as a road base material. It can be mixed with lime and water to produce a cement-like material or mixed with cement itself. However, the supply currently far exceeds the demand for this type of material (Santhanam et al., 1979).

Mining wastes, tailings, and water drainage present pollution problems of high acidity, high dissolved and suspended solids and high metal concentrations. The tailings often contain a large amount of sand and fine material which is carried by water, creating a pollution problem. Tailings from toxic metal ores must be disposed of in a site specifically designed and maintained to properly handle such wastes.

2.5 Discussion of Waste Fluids

The durability and service life of a given liner depends to a great extent upon the specific fluids with which it is in contact from the time it is originally placed. It must be recognized that, in almost all disposal impoundments, the waste and the waste fluids are continually changing in composition with time. Consequently, an important consideration in the operation of a disposal site is that measures be taken to minimize the variation in the character of the waste, as there is no single lining material which can resist all wastes.

Liners can vary greatly in chemical composition from compacted soils and clays to highly crystalline polymeric materials which are highly chemically resistant and have very low permeability. Similarly the wastes, as indicated in the above discussion in this chapter, can vary from highly polar solvents, like water, through highly nonpolar materials, like lubricating oils and hydrocarbon solvents. Most of the wastes will probably contain water as a principal carrier. All materials have, to a certain degree, a solubility in water; consequently, contaminants or pollutants can be carried in the water. Also, many solvents can be totally miscible with water. The complexity of wastes can result in combined effects with respect to many of the liners. Furthermore, even minor amounts of the organic materials in the water or leachate can preferentially combine with organic liner materials, e.g. asphalt or all of the polymeric materials.

Dissolved organic constituents, even in minor amounts, will gradually dissolve in the organic liners and, over extended periods of time, may cause the

TABLE 2-11. TRACE ELEMENT CONTENT[a] OF SAMPLES FROM COAL FIRED ELECTRIC POWER GENERATING STATION[b]

Element	Coal (ppm)	Bottom ash (ppm)	Lime-stone (ppm)	Waste (ppm)	Ash pond liquor (mg/L)	Scrubber liquor (mg/L)	Makeup water (mg/L)
Antimony	.33	3.4	3.2	6.7	.03	.06	.005
Arsenic	4.6	3.9	2.7	6.7	.004	<.0004	.002
Barium	100	300	<30	<20	<.3	<.3	<.3
Beryllium	.16	4.5	.17	1.8	.001	.004	.001
Boron	96.9	53.8	17.4	41.8	1.03	6.17	.414
Cadmium	7.9	1.6	.65	25	.04	.009	.0007
Chromium	.45	5.5	<.80	5.2	<.0002	<.0002	<.0002
Copper	41.5	130	2.4	65	.01	.01	.006
Fluorine	372	95.7	117	266	10.4	15.9	.66
Germanium	4.5	.25	.11	5.9	.07	.39	.02
Lead	41	21	13	290	.008	.010	.014
Manganese	142	491	290	340	1.1	2.0	.15
Mercury	.322	<.010	.020	0.10	.0015	.002	<.001
Molybdenum	.41	1.4	12	9.6	.10	.27	.02
Nickel	51.7	187	6.20	75.2	11	.25	<.01
Selenium	3.2	.51	.22	2.1	.015	.18	.0012
Vanadium	<12	<24	<160	<100	.2	.2	.2
Zinc	780	798	48	2050	2.5	4.2	.04

[a] Values represent the average of duplicate determinations. Solid samples are reported on a dry basis; water and liquor samples on an as-sampled basis.

[b] Santhanam et al., Vol. 3, 1979.

failure of a liner based upon organic materials. There are indications that organic waste liquids can also have major adverse effects on some soils and clays.

The character of wastes and their effects on liners are discussed further in Chapter 4.

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CHAPTER 3. LINING MATERIALS AND LINING TECHNOLOGY

3.1 Introduction

The purpose of lining a waste disposal site is to prevent the potentially polluting constituents of the waste from leaving the site and entering the groundwater or surface water system in the proximity of the site. The pollutants, as discussed in Chapter 2, include organic and inorganic materials, solids, liquids, gases, and bacteriological species. In their performance liners function by two mechanisms:

a. To impede the flow (flux) of the pollutant and pollutant carrier, usually water, into the subsoil and thence into the groundwater. This requires a construction material having low permeability.

b. To absorb or attenuate suspended or dissolved pollutants, whether organic or inorganic, in order to reduce the concentrations so that they fall within the ranges set by the EPA for groundwater. This absorptive or attenuative capability is dependent largely upon the chemical composition of the liner material and its mass.

Most liner materials function by both mechanisms but to different degrees depending on the type of liner material and the waste fluid and constituent. Membrane liners are the most impermeable of the liner materials, but have little capacity to absorb materials from the waste. They can absorb a relatively small amount of organic material but, due to their small mass, their total absorption is small. Soils can have a large capacity to absorb materials of different types, but they are considerably more permeable than a polymeric membrane. However, the greater thickness of the soil can result in low flux through the liner. The choice of a particular liner material for a given site will depend upon many factors which are discussed throughout this Manual. In this chapter, the major candidates for use as liner materials are discussed.

For the purpose of this manual, we consider a liner to be a material constructed or fabricated by man. Such a definition includes soils and clays having low permeability which are (1) either brought to a site or available on the site and (2) compacted or remolded to reduce permeability and increase strength.

Liners can be classified in a variety of ways, such as construction method, physical properties, permeabiliity, composition, and type of service. These classifications are presented in more detail in Table 3-1. In this chapter, the various types of liners are discussed in the following classes:

- Soil and clays
- Admixes
- Polymeric membranes
- Sprayed-on liners
- Soil sealants
- Chemisorptive liners.

For each type of lining material, characteristics and general features of the liner and the advantages and disadvantages are discussed.

TABLE 3-1. CLASSIFICATION OF LINERS FOR WASTE DISPOSAL FACILITIES

A. BY CONSTRUCTION:

- Onsite construction:
    - Raw materials brought to site and liner constructed on site.
    - Compacted soil.
    - Mixed on site or brought to site mixed.
    - Sprayed-on liner.
- Prefabricated:
    - Drop-in polymeric membrane liner.
- Partially prefabricated:
    - Panels brought to site and assembled on prepared site.

B. BY STRUCTURE:

- Rigid (some with structural strength)
    - soil
    - soil cement
- Semirigid
    - Asphalt concrete
- Flexible (no structural strength)
    - Polymeric membranes
    - Sprayed-on membranes

C. BY MATERIALS AND METHOD OF APPLICATION:

- Compacted soils and clays.
- Admixes, e.g. asphalt concrete, soil cement.
- Polymeric membranes, e.g. rubber and plastic sheetings.
- Sprayed-on linings.
- Soil sealants.
- Chemisorptive liners.

3.2 Soils and Clay

3.2.1 Introduction

Due to their general availability, clayey soils should be considered the first alternative for a waste confinement liner. Based on engineering, environmental, and economic criteria, an initial analysis should assess whether the native soil present at a site can be used to produce an effective liner. If the result of such an analysis is negative, other alternatives must then be explored.

A soil liner is the soil material which is native at or near the waste disposal site and which has been properly treated, remolded and/or compacted so that a flow-impeding layer of low permeablity to wastes has been obtained.

The compacted soil liner has to be designed following a proper environmental analysis. Criteria have to be set forth and the functionality of the soil liner has to be assessed. If the environmental conditions have been analyzed and understood, and the design complies with all environmental requirements, failure should not occur.

3.2.2 Fundamental Properties of Soils

3.2.2.1 Chemistry and Mineralogy of Soils and Clays

Soils to be used as liners at waste disposal facilities must contain a relatively large proportion of fines, i.e. particle size less than 2 μm. For a broad range of soils a close correlation between soil permeability and clay (less than 2 μm) content has been observed; soils exhibiting low permeability generally contain a large proportion of fines. The minimum amount of clay size particles required in soil to yield a good soil liner is 25-28% by weight.

The distinction between clay and nonclay made at particle size equal to 2 μm is based on the observation that clay minerals are heavily concentrated below this size, while nonclay minerals constitute the bulk of soil solid phases above this particle size.

This general rule deserves a more careful consideration. When examining particular clay minerals, one finds that typically each clay mineral has a preferred particle size distribution in the range less than 2 μm; since the colloidal character of a particle increases with the decrease in size, different clay minerals will have different degrees of colloidality. Also of significance is the real colloidal range, considered to be from 1 nm to 1 μm (Daniels and Alberty, 1963, p.573). Due to the relatively large surface area of the clay size fraction in a clayey soil, the mechanical behavior of such a soil is dependent on the surface physico-chemical characteristics; and since these are determined by the clay mineral chemistry, the bulk behavior of a clayey soil can be understood only if the chemistry and the mineralogy of the clay fraction are carefully considered.

Of importance in the clayey soil functioning as a liner are the changes in interlayer spacing and the consequent volume changes exhibited by different clay minerals when exposed to organic or inorganic chemicals that are likely to appear in a waste impoundment fluid. Table 3-2 presents some of the essential features of kaolinite, illite, and montmorillonite, the three clay mineral species most likely to constitute the bulk of the clay fraction of many soils. These three species are discussed briefly below.

TABLE 3-2. TYPICAL VALUES FOR PROPERTIES OF KAOLINITE, ILLITE, AND MONTOMORILLONITE[a]

Clay mineral	Particle thickness			Charge[c] per formula weight	Surface area, m^2/g	Exchange capacity meq/100g	
	Con-tracted (nm)	Hydra-ted[b] (nm)	Volume change, %			Cation	Anion
Kaolinite (nonexpansive 1:1 lattice)	200.0	202.0	1	0	8	10	pH dependent
Illite (nonexpansive 2:1 lattice)	20.0	22.0	10	1.0	80	15	pH dependent
Montmorillonite (expansive 2:1 lattice)	2.0	6.0	200	0.5	800	100	pH dependent <5

[a] Brown and Anderson, 1980, p 124.
[b] Four water layers absorbed for each available basal surface.
[c] Units are multiples of electrostatic units (esu). One charge = 4.8029×10^{-7} esu.

Kaolinite particles have a small negative surface charge. Adjacent layers of this mineral are strongly held together by hydrogen bonding. For this reason kaolinite exhibits little interlayer expansion; adsorption can occur only on external particle surfaces. Edges of the crystal exhibit broken bonds which give rise to a small number of highly pH-dependent positive or negative charges.

Illite is characterized by the presence of "fixed" potassium ions in a twelve-fold coordination between two planes of oxygen atoms. The high charge of the crystal unit combined with the perfect fit of the potassium ion in its cavity, promotes rigidity and impedes water penetration between crystal layers; consequently a limited swelling occurs. A second very important aspect of the presence of "fixed" or "nonexchangeable" potassium between successive layers is that, despite its high negative charge, i.e. its potentially high exchange capacity, the real cation exchange capacity (CEC) is only a fraction of the potential one. The real CEC of the illite is consequently intermediate between the CEC of kaolinite and that of montmorillonite.

Montmorillonite has characteristically the smallest particle size of the three clay minerals. Typically the site of the negative charge is in the inner octahedral layer in which incomplete isomorphous substitution occurs; this generates a minimal cohesion between successive 2:1 layers, resulting in a very receptive and chemically active structure. Montmorillonite readily absorbs polar organics or positively charged organic groups or inorganic ions. It exhibits the greatest surface area, CEC, and shrink-swell potential. In water, it can absorb on its interlayer surfaces 300% of its solid phase weight and consequently has the capacity for large shrinkage if the water is displaced by other fluids that yield a lower interlayer spacing.

Permeability of the three clays as a function of exchangeable calcium and sodium contents is shown in Figure 3-1. Yong and Warkentin (1975) observed that clays with divalent cations are, in general, more permeable than those with monovalent cations adsorbed onto interlayer surfaces. This effect is the same in all clays but is most pronounced in montmorillonite.

Calcium montmorillonite adsorbs interlayer water to yield a stepwise increase in basal spacing from 1 nm (oven dry state) to about 2 nm (Theng, 1979). This increase corresponds to a 1 nm thickness of water per surface when Ca-montmorillonite is fully expanded. With divalent cations such as calcium or magnesium adsorbed to its surfaces, montmorillonite resists dispersion and remains flocculated. While the flocculated state usually yields a higher permeability, its structure is more stable than the easily dispersed sodium saturated montmorillonite.

Sodium montmorillonite adsorbs interlayer water to yield a basal spacing from 1 nm (oven dry state) to over 5 nm (Theng, 1979). This represents a thickness of 4 nm for water on each surface. While this much interlayer expansion would at first appear advantageous for its ability to reduce clay liner permeability, the expansion is reversible and hence sodium montmorillonite is susceptible to shrinkage if it dries. Another problem with sodium-montmorillonite is that when it is fully expanded, it is susceptible to dispersion and internal erosion (see 4.3.3., "Piping"). A dispersed clay that lacks structural strength could flow as a viscous fluid if it is free to expand. This condition may cause problems such as loss of strength in waste impoundment side walls.

Quirk (1965) found the permeability of sodium saturated montmorillonite decreased when the concentration of NaCl in the percolating solution was decreased. A similar clay saturated with calcium showed no appreciable decrease in permeability with decreases in the calcium concentration in the percolating solution. Quirk and Schofield (1955) showed larger permeability decreases with decreasing electrolyte concentration in the percolating solution for clays with higher percentages of sodium on the exchange sites.

Blackmore and Marshall (1965) found that increasing sodium chloride concentrations in a fluid passing through a film of sodium saturated montmorillonite suppressed the double layer. The diminished double layer effect inhibited swelling while it decreased interlayer spacing and permeability.

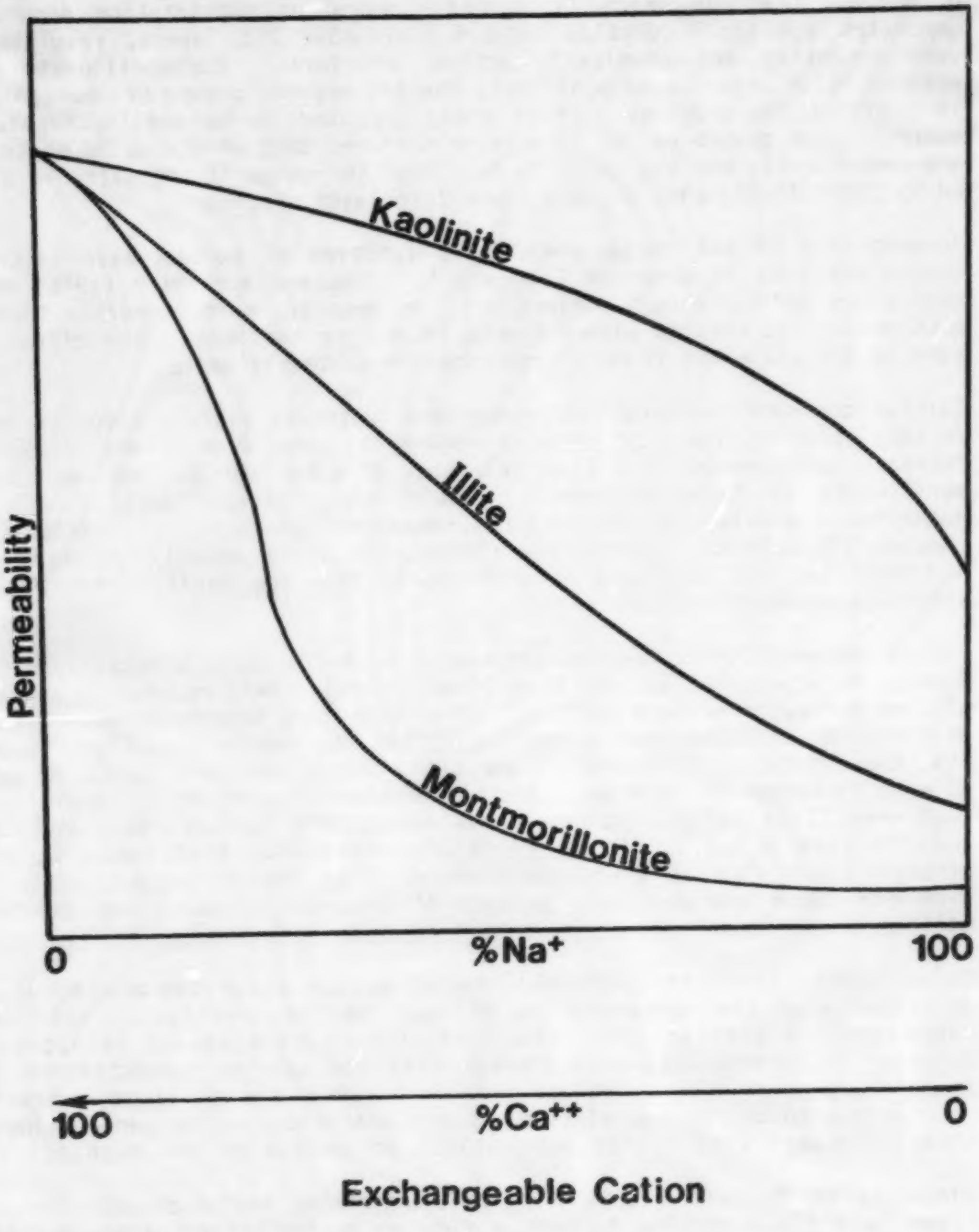

Figure 3-1 Relative permeability values for three clays with variable percentages of calcium and sodium on exchange sites (Yong and Warkentin, 1975).

3.2.2.2 Attenuation Properties of Soil Liners

A clayey soil liner below a potentially polluting waste can attentuate a pollutant by reducing the level of contamination (if present), spreading the contamination over a much longer period, and lowering considerably the maximum value of contamination, i.e. highest discharge of contaminant per unit area and time during the period of operation. The term "attenuation" at the same time implies that a soil liner cannot be an "absolute" liner. This point is illustrated schemetically by Figures 3-2 and 3-3 for which the following assumptions were made:

- The rate of contamination is defined as the amount of polluting species passing through a unit area per unit time, e.g. grams per square meter per day.

- The rate of contamination is evaluated in all cases at a depth L from the waste interface. The depth L is also taken as the thickness of the liners in cases B through E, inclusive.

- The permeability of the liners in Cases B through E, inclusive, is assumed to be the same.

- The permeability of the native soil is assumed to be greater than that of the clayey soil liners.

- The absorptive capacity for the polluting species in Case C is less than the corresponding capacity in Case D.

- The absorptive capacity of the liner in Case E is greater than the total mass loading of polluting species of the single load situation.

- The single unit load situation is defined as a set, finite amount of polluting species at a given hydraulic gradient which, over time, will approach zero as the polluting species passes through the soil and/or liner and is not replenished.

- The constant, continuous waste loading is defined as the maintenance of a given constant concentration of polluting species at a given hydraulic gradient over time. This implies replenishment of the polluting species in the waste.

- The analysis assumes saturated flow.

- The analysis assumes that the waste does not damage the liner or its structural integrity.

Shown in Figure 3-3 are rate curves for the two loading conditions defined above. Analysis of Figure 3-3 reveals that Case A, as expected, has the highest flux of pollutant contamination, reached within the shortest relative time period. In the situation of single unit loading a plateau is reached, continues for a period of time and then drops off as the amount of pollutant

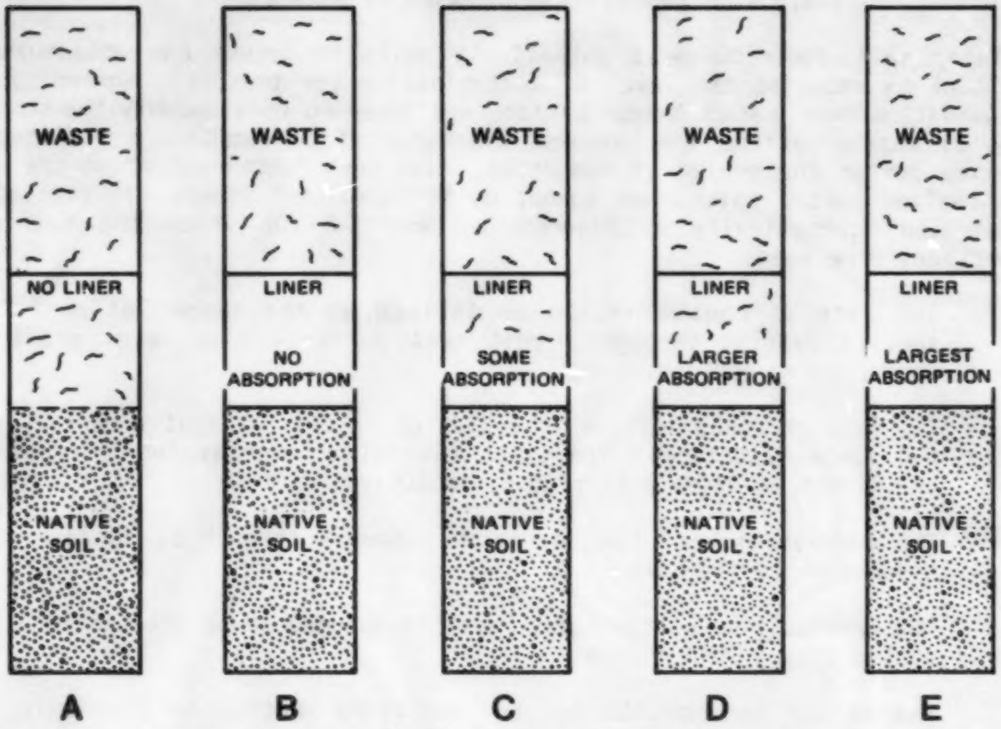
WASTE
WASTE
WASTE
WASTE
WASTE
NO LINER
LINER
NO ABSORPTION
LINER
SOME ABSORPTION
LINER
LARGER ABSORPTION
LINER
LARGEST ABSORPTION
NATIVE SOIL
NATIVE SOIL
NATIVE SOIL
NATIVE SOIL
NATIVE SOIL
A
B
C
D
E

Figure 3-2. Attenuation of polluting species by soil liners of different absorptive capacities. Schematic representation of each liner situation under consideration.

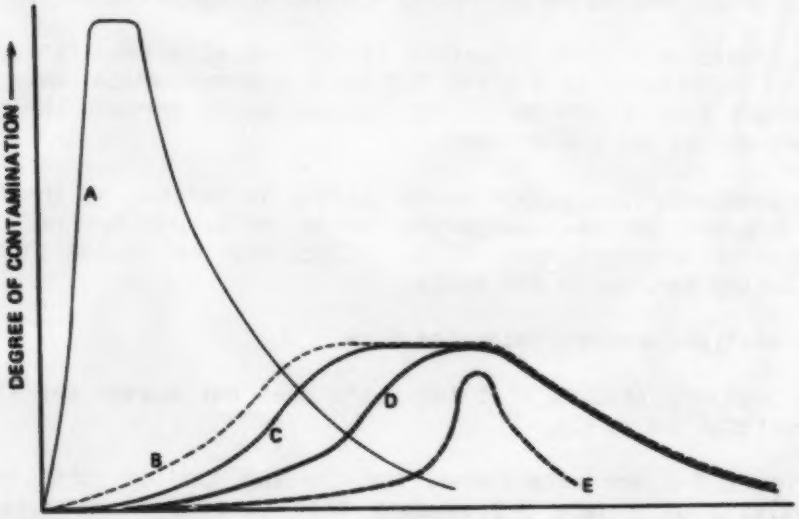

Figure 3-3. The rates of contamination of soil liners from Figure 3.2 at the depths equal to the thickness of the liners.

remaining decreases. In the situation of constant, continuous loading, the plateau is maintained due to the steady loading condition. In Case B, a liner is present which functions solely to impede flow by reduced permeability.

The distinction between A and B is one of intensity of contamination; the capacity of contamination is the same since the integrals below the two curves for times between 0 and t are assumed to be equal. The factors controlling the degree of contamination are mainly physical (flow properties) inasmuch as absorption is assumed not to affect them drastically. In drawing these two curves, one assumes that the contaminant concentration of any polluting species follows the same pattern; the flat plateau represents the situation of the maximal concentration controlled by the characteristic dissolution/precipitation reactions of the effluent. All in all, the permeability differential has the effect of diminishing the intensity factor but leaving the capacity of contamination unaltered, only a retardation effect is accomplished.

In examining Cases C and D, it can be seen that reaching the maximum rate of contamination is delayed due to the absorptive capacity of the liners. At any time prior to attaining the maximum rate plateau the difference in the rate curves reflects the magnitude of absorptive capacity of each liner. This absorptive capacity can be defined as the altering of the chemical composition of the waste fluid with respect to the polluting species such that the species is irreversibly retained in the liner. Characteristic curves like C and D will be generated depending on the degree of retention of the polluting species by the liner. If the relationship between a particular contaminant and the liner is so large that the pollutant is almost totally retained, then no plateau will exist for such a curve for single loading and a situation similar to that described for Case E will result. The characteristic curve shown by Case E reflects "leakage" in the system. In the situation where constant, continuous loading is applied, the characteristic curve for Case E after a relatively long period will approach the plateau level of Cases B, C, and D.

Further analysis of Figure 3-3 shows the rate differential of the characteristic curve plateaus for the constant, continuous loading situation. This differential, given the assumptions stated previously, is mostly a function of permeability of the soil versus the liner.

Attenuation and cation exchange capacity -

The term "attenuation" is sometimes erroneously linked to metallic trace elements through the well-known cation exchange properties of soils; this connection can be grossly misleading on at least two bases:

a. Soil cation exchange properties are revealed by true exchange reactions. A cation can be adsorbed and temporarily stored into the liquid-solid interface; upon the decrease of concentration in the liquid phase, it will be again released. Consequently, if an exchange would have been present in Soil B, then the degree of contamination versus time relationship should have been a mirror image of Curve B, but slightly displaced to the right on the time scale. The picture described by Soil C does not correspond to such a situation. Curve C describes the situation in which the retention of the cation was permanent. Although these reactions are known in soil chemistry (for metallic species like K, Li, etc.), the engineer designing a waste disposal site should not rely on them.

b. For the same ionic composition and strength of waste effluent and the same activity of a particular cation, the larger the cation exchange capacity of a soil, the larger the amount of the element temporarily stored. However, this amount is so dependent on the chemistry of the effluent (its purity with regard to the particular element considered, ionic composition, strength, secondary mineral formation (precipitation/dissolution), the presence of chelating agents, complex formation with different than assumed ionic forms, etc.) that the effect of the magnitude of the exchange capacity is almost totally offset.

Modeling the functionality of complex systems has been done (Lowell, 1975). Such an analysis will require an accurate assessment of the interaction between the particular waste and soil considered. This analysis can be only obtained by setting up and performing a research program on the matter.

3.2.3 Engineering Characteristics of Soils and Clays

3.2.3.1 Atterberg Limits

Although empirical, the Atterberg limits are a powerful tool in assessing, as a first approximation, the mechanical behavior of a clayey soil. This is reflected in the emphasis on plasticity parameters in the classification of fine soils using the Unified Soil Classification System (Appendix I).

The consistency of a given soil differs with moisture content. Clayey soils, which are the types of soil required for liners, represent the most vivid example in this respect. The effect the degree of hydration of clayey soil has on its compressive strength is well known. The plastic limit and the liquid limit are tremendously valuable in engineering work for characterizing and assesing soils. The plastic limit is the soil moisture content just below which the soil is friable and just above which the soil is plastic (it can be molded as a paste which exhibits a permanent set). The liquid limit is the soil moisture content just below which the soil is barely plastic (although creep deformation can very easily occur) and just above which the soil flows (it behaves like a suspension). At the liquid limit, soil behavior is a blend of plastic deformation (tends to cease deformation upon stress removal) and liquid flow (deforms freely after stress removal).

Though the plasticity test generates results in terms of mechanical behavior, it can furnish considerable information because it is simultaneously a chemical and a physical test. It can furnish information regarding the reaction of clay and water, a reaction which is determined largely by the chemical and mineralogical properties of the clays in the soil.

The "Atterberg Limits" is the test which will help classify the soil and, consequently, will heavily weigh in the decision-making process: it will answer the question whether the waste disposal site is covered by a soil which can be improved in a soil liner. Soils which belong to the groups CL or CH should be considered the most suitable. Probably the most favorable soils are those with a liquid limit between 35 and 60, placed above the A-line in the PI versus LL chart of the Unified Soil Classification (Appendix I).

The informative power of this test can be increased by coupling it with knowledge of the clay content, i.e. the percentage of particles less than 2 μm in diameter. The concept of "activity", introduced by Skempton (1953), normalizes the plastic effect per unit weight of clay. Since this has been found to be characteristic of any particular clay (Skempton, 1953) depending on the type of clay (Mitchell, 1976), quick information regarding the type of clay in the soil can be obtained without resorting to x-ray analysis or other more quantitative mineralogical analyses.

The Atterberg limits are the result of a reaction between the clay phase of a soil and water. Consequently, the composition of both soil and the water has an affect on the plastic behavior of the soil. To bypass the difficulty of using fluid with unknown and always different composition, the ASTM methods recommend the use of distilled water which standardizes the procedure, but by so doing the methods alter the magnitude of the plastic effect. In most engineering work this procedure may not lead to significant errors. However, a soil liner may be subjected during service to very aggressive liquids, in many instances concentrated electrolyte solutions. Consequently, the use of a moderately high electrolyte solution, such as 0.01 N $CaSO_4$ rather than distilled water is recommended.

If the soil is suspected of being chemically sensitive (for instance a soil containing more than 20%, by weight, montmorillonite clay), we recommend performing Atterberg Limits by using both distilled water and 0.01 N $CaSO_4$ on duplicate samples. Eventually, an actual waste liquor can be simulated and used as a molding fluid.

The power of this test lies in the fact that it is a simple, routine, and relatively inexpensive test and, when using different fluids with different compositions, valuable information can be gained regarding to the buffer capacity of the soil, i.e. its ability to resist physico-chemical alterations and perhaps mechanical changes.

3.2.3.2 Compactibility

The properties of a soil, particularly those of importance for a soil liner, can be significantly altered by mechanical compaction. From the standpoint of liners, the most important effect of compaction is upon the permeability of the soil.

The fundamental aspects of soil compaction were established almost a half a century ago by R. R. Proctor (Burmister, 1964). It is well known that any soil has a unique laboratory density/moisture relation, i.e. Proctor curve, if compaction conditions are held constant. The relationship defines a unique density value (maximum density) and a corresponding moisture content (optimum moisture content) which are essential parameters for design consideration.

Because construction equipment and methodology can be variable and complex, standardizing uniquely the testing conditions will not necessarily generate similar information for the field work. Thus, the modified AASHTO compaction test procedure was introduced (McDowell, 1946). Based on this test a large amount of information was collected on the effect of the field compactive effort on the density-moisture content relationship.

In respect to this relationship, it is found that increasing the compactive effort increases the maximum density and decreases the optimum moisture content. Also quite well established is the effect of soil mechanical composition on the shape and position of the density-moisture content function:

a. The more granular the soil (the more sandy it is), the higher the maximum density and the lower the optimum moisture

b. The finer the soil (the more clayey it is), the less defined the maximum density and the flatter the curve of the density as a function of moisture content.

Since the poorly defined peak on the density curve is a characteristic of soils with more than 25-30% clay and since soils containing less than this proportion of clay are tentatively excluded from construction of soil liners, it becomes quite evident that:

a. The quality control for the density achieved in the field requires considerably more attention and skill in the case of clayey soils.

b. The density obtained in the field should be only the first stage of the field testing program; other tests must be conducted.

By superimposing the conclusions of the test results on general information, the design should optimize the field compaction procedures to be used by the construction contractor.

It is well known that any increase of compactive energy, any increase in persistence of the applied energy, or any decrease of the layer thickness results in a soil with a higher density. This constitutes basic information. The test results have to quantify the interaction among these three factors.

The uniformity of moisture content of the undisturbed soil which is to be compacted, is of major significance when light rather than heavy rollers are being used. Heavy rollers seem to be more effective in compacting soil in a field of variable moisture content (Burmister, 1964). On the other hand, working the soil in the high moisture range with heavy rollers can result in the development of positive pore-water pressures, an effect which seems to be particularly true for highly plastic clayey soils (Porter, 1946). Under such compaction the pore pressure which develops in the clay cannot dissipate because of the low permeability of the clay. This aspect of the problem is important since, for reasons which will be discussed in Section 3.2.3.4, the compaction operation in the field has to be conducted in the range of high moisture content.

Compaction which results in generation of positive pressures and consequently prevents densification is called "over compaction" (Turnbull, 1964; Holtz, 1964). To prevent its occurrence, or at least to minimize its dimension, a compaction procedure called "stage compaction" is recommended (Burmister, 1964). According to Burmister, stage compaction is the "principle of matching the supporting value and compactibility of soil layers by appropriate compactive effort, weight, and efficiency of roller for two or more stages of compaction in order to insure efficiency and effectiveness of compaction at all stages". The principal reason for recommending stage compaction is that stage compaction uses most of the compactive effort in densification rather than shear deformation and thereby will increase the efficiency of that effort. Indeed, when the strength of the compacted soil is the primary concern, shear deformation is a wasted effort; but, in our case, lateral displacement of the soil below the compacting implement is useful and is discussed further in Section 3.2.3.4. Despite its limited use (since our primary concern is flow impedance rather than strength), the designer should consider stage compaction as a strategy in compacting the soil, because any densification should yield a soil blanket with a lower permeability. In compacting highly plastic clayey soils, the stage compaction may very well be the only way to deal with this material. It has been also found that, in the case of plastic soils, the thickness of the rolled layer should be decreased (Porter, 1946).

In general, when the compaction is performed in the field, at a moisture content over the optimum, operation limitations restrict using heavy rollers; in this case the desired density has to be achieved by increasing the number of passes over the compacting layer. Some experimental results have also shown that increasing the foot-pressures used and decreasing the layer thickness in the same proportion result in equally dense soils (Sowers and Gulliver, 1955).

All this information is based on empirical considerations. Behavioral exceptions may be found and it is the role of the designer to identify and to use them advantageously.

The design specifications must define the desired compaction in terms of relative density or percent compaction and should be stated as "percentage of the laboratory maximum density". This is particularly true in the case in which the investigated area is covered by different soil types.

3.2.3.3 Volume Changes

Upon remolding and compaction a soil with a particular density can be obtained for which a set of relevant flow properties can be ascertained. Since a certain fraction of the soil bulk volume will be filled with air at the end of the compaction operation, the pore water pressure will be on the negative side, i.e. water will be held under tension in soil. The presence of a soil matrix will reduce the value of the water potential below the reference level (pore-water potential equal to 0). As indicated by Seed et al. (1962), the basic factors controlling swelling in a soil that is not fully saturated are those responsible for generating negative pore-water pressures. As a general rule, all other factors being equal, the lower the pore pressure (the larger the absolute value in the negative range), the more prominently manifested is the swell of the soil.

The affinity of soils for water is expressed by the moisture characteristic (moisture-retention water characteristic) curve in which the equilibrium moisture retained at different suctions (negative pore-water pressures) is measured. The measurement of negative pore-water pressures in samples freshly compacted in the laboratory should provide the designer with valuable qualitative information concerning the swell/shrink properties of the soil.

Since causes of negative pore-water pressures in unsaturated soils are explained in terms of soil-matrix intrinsic properties (if the pore fluid is at a standard reference temperature and osmotic potential), the affinity of the soil for water is measured and expressed as "matric potential".

Most often soil strength is defined as the sum of a cohesional component and a frictional one, with the first component being viewed as relating to the soil and the second one being ascertained only when normal loads are operative. Similarly, one can look at positive pore-water pressures as those whose manifestation depends on environmental conditions, while the matric potential, similar to the cohesional strength, is a characteristic of the soil. Finally, one should accept the point of view that there is a relationship between the swell-behavior of soils and the resistance opposed by soils when compacted (Meade, 1964).

For design considerations, volume changes are important because they occur over time, after the placement of the soil liner. The design parameters have to be established as a result of a careful consideration of swell behavior and its influence on soil flow properties. Consequently, a prediction of the swell pressure and swell potential of the soil has to be made. A detailed development and analysis of swell behavior is presented in Appendix VI.

The effect of waste chemistry on volume changes and, consequently, on soil flow properties is discussed in Section 4.2.2.3.

3.2.3.4 Permeability

Soil permeability, K, is a numerical measure of the ability of the soil to transmit a fluid. When water is the permeating fluid through the soil, it is often called hydraulic conductivity. K can be determined using Darcy's relationship:

$$J = K\Delta H$$

where J = volume of fluid passing through unit cross sectional area of soil per unit time,

ΔH = hydraulic gradient, i.e. the rate of change of hydraulic head in the direction of flow.

When H is expressed as "weight hydraulic potential" (units of length, L) and J as volume per area times time (units of LT^{-1}), the permeability is expressed in the c.g.s. system as cm sec^{-1}.

Darcy's law is a useful relationship which has been widely used to determine K. Its validity has been questioned for very dense clayey soils because the fluid permeating the soil does not behave as a Newtonian liquid and the soil does not preserve a rigid structure (due to osmotic and seepage forces). Although the reputation of this relationship has been eroded, it still is the main relation describing flow in a clayey soil; in qualitative terms it will always be accepted, since, the larger the hydraulic gradient, the larger the resulting flux.

Because K depends on properties of both components, soil and fluid, the term "soil permeability" is not justified; to remove the effect of fluid properties, the notion of "intrinsic permeability coefficient" (IPC) is introduced; thus:

$$K' = K \frac{n'}{G}$$

where K' = IPC expressed in the c.g.s. system as cm^2

K = permeability (cm sec^{-1})

n' = kinematic viscosity (cm^2 s^{-1})

with $$n' = \frac{n}{\rho}$$

n' = viscosity (g cm^{-1} s^{-1})

ρ = density (g cm^{-3})

G = gravitational constant, 981 cm s^{-2} at 45° latitude.

It can be observed that the fluid viscosity normalizes the resistance to flow due to the fluid cohesiveness, while the fluid density normalizes the effect of gravity on fluid flow. In principle the use of IPC values permits the comparison of K values of several soil samples of the same soil, when permeated by different fluids.

At G = 981 cm s^{-2}, the relation between K and K' for water at 25°C is expressed by the equation:

$$K' = 0.91 \times 10^{-5} K$$

where K' is expressed in cm^2 and K in cm s^{-1}.

In the case of lined disposal sites, the soil liner may be contacted by fluids with very exotic chemical compositions. In this case the kinematic viscosity correction which is operated on K to produce K' is a small improvement.

The primary goal of constructing a blanket with low permeability is carried out in the field by the compaction of soil. Through this operation a dense soil material is obtained with a lower void ratio, since, according to both Taylor-Poisseuille and Kozeny-Carman relationships (Lambe and Whitman, 1979), K is proportional to $e^3 (1+e)^{-1}$ where e is the void ratio.

All other factors being constant, a reduction in the void ratio should result in a lower permeability, K. The reduction of the void ratio upon compaction promotes two changes in the soil: a decrease of the effective area available for flow (effective pore area being measured perpendicular to the flow direction), and decrease of the median pore size value. According to the capillary model, the flux (LT^{-1}) is proportional to the second power of the radius.

A very important consequence of the K-e function is that soils being particulate media and K being always measured on specimens for which the sample size is much greater than average particle size, K will always be positive since the condition e=0 contradicts the definition of a soil as a porous medium. Consequently, truly impermeable soils (K=0) do not exist.

Most undisturbed soils have permeabilities in the range of 10^{-7} cm s^{-1} to 10^{-3} cm s^{-1}. Intrinsic soil characteristics as well as naturally occuring environmental conditions play a tremendous role in the resulting broad range of permeabilities encountered in nature. If one looks over the whole range of permeability values of undisturbed soil, the particle size characteristics seem to be the most relevant; soils with more than 25-30% clay size particles are concentrated in the lower range of permeabilities, i.e. 10^{-7} cm s^{-1} to 10^{-5} cm s^{-1}.

However, if one tries to correlate K with the percentage of clay size particles over that narrow range of permeabilities, the relation between particle size and permeability becomes less significant; i.e. other factors become relatively more significant in their effect upon flow properties. For one thing, the types of clay minerals present in the clay fraction and, the particle size distribution in the less than 2 μm fraction, play a very important role. The interlayer chemistry of the crystal-unit, the susceptibility of the particles to disperse or flocculate upon hydration and/or mechanical remolding and the average size of a typical tactoid (agglomerate of clay particles), all are factors which have a profound effect upon soil-water flow characteristics; they can alter the K value by as much as two orders of magnitude for otherwise apparently very similar soils. Since this can make the difference between using or not using a particular soil as a liner, the site-designing group has to obtain pertinent information regarding these factors.

The physico-chemical behavior of a clayey soil has such an overwhelming effect upon soil permeability because of the dependence of soil clay structure on physico-chemical properties and the effect of the structure on permeability.

If a soil clay fraction would have a fixed structure, totally insensitive to changes in hydration conditions and stresses applied, then the K versus w (water content) function would be a mirror change of the γ density versus w function with the lowest permeability corresponding to the maximum density, on the γ vs. w graph. All of the physico-chemical factors mentioned have a drastic effect on clays, particularly in the case of montmorillonite clays; they have a very sensitive structure and the permeability of a montmorillonite soil is far from being a simple function of density.

Lambe (1958) showed that the permeability of compacted clays is much greater on the dry compared to the wet side of the optimum. He also concluded that the higher the compactive effort, the smaller the difference between the ranges of permeabilities achieved on both sides of the optimum. Clay compacted dry-of-optimum was found to have an "open", flocculated structure, while the wet-of-optimum tends to have a dispersed structure; this effect determines the flow properties to such an extent that almost nothing is left from the generally accepted belief that soil permeability and density are inversely related. Lambe (1958) also noted that on the dry-of-optimum side, there seems to be a threshold pressure beyond which the clay structure tends to reproduce the structure of the "wet"-clay, i.e. to orient its particles parallel to a preferred plane.

Some of these conclusions were carefully investigated in the sixties by Mitchell et al. (1965). In carrying out the investigation on a silty-clay (the more general term "clayey-soil" is often used for silty-clay) for which some of its mechanical properties were very well established, Seed and Chan (1959) confirmed the above conclusions and new effects were simultaneously revealed. Thus, combining different compactive efforts with different moisture contents to produce a unique, quite high density soil (108 lb/ft^3 or 1.732 $g\ cm^{-3}$), the permeability showed a slight increase with the water content, on the dry side of optimum.

When samples were compacted again by kneading compaction using the same compactive effort at different combinations of w and γ, the slight effect of K increase with density and moisture content in the dry-of-optimum range was still present; but when the experiment was repeated with a different soil (over a more narrow range of moisture content) the effect was not present, i.e. samples prepared dry-of-optimum indicated a "normal" drop of permeability with an increase in density.

The research conducted by Mitchell et al. (1965) indicated that when samples are compacted at a moisture content below the optimum moisture, the K versus w function depends on so many factors that, if precise information is needed, testing of the soil is the only answer; it is essential to reproduce the field conditions.

Any further increase in moisture content beyond the optimum moisture, results in a tremendous drop in K-value. Furthermore, the results presented by Mitchell et al. (1965) indicate that the choice and use of a particular compacting effort is significant to the K-value, particularly on the wet side of optimum. Using a very high moisture content and compacting their silty-clay soil using a kneading compactor at the same void ratio, the authors obtained a large range of K-values (over two orders of magnitude) using different compactive efforts. The conclusion is that by compacting the soil at a very high moisture content the permeability can be significantly decreased by structural arrangements of soil (clay) particles rather than diminishing the total void space of the soil.

The picture presented above refers to laboratory soil specimens compacted with a kneading compactor, which has a better resemblance to the compaction of soils in the field compared to static compaction (Lambe and Whitman, 1979). It has been conclusively shown that particle preferential orientation and consequently permeability reduction upon compaction is more prominent in samples which were compacted using a kneading compactor rather than impact, vibratory, or static compaction (Seed and Chan, 1959; Mitchell et al., 1965). But it has been pointed out by Mitchell (1956) that clays, and presumably clayey soils, are quite different in their behavior upon remolding. In general, clay deposits which are believed to have been formed in marine or brackish environments, are quite efficiently remolded, i.e. a preferred orientation upon remolding can be achieved relatively easily; this conclusion seems to be particularly true for clays which have been precompressed in nature at very low stresses, e.g. the Scandinavian sensitive clays. The clay deposits, which have been sedimented in fresh waters and have been highly precompressed, e.g. the Texas and New Orleans clays investigated by Mitchell, cannot be efficiently remolded since they already have an oriented structure to start with, i.e. in their undisturbed state. Consequently, in establishing the technology to be used for producing a soil liner, the designer should have information on:

a. Natural preconsolidation pressure of the soil cover.

b. Conditions at formation or deposition of the soil considered.

This kind of information, associated with proper testing to reveal the sensitivity upon remolding of the soil, should provide the designer with the knowledge required to produce a soil-liner with a lower permeability.

Since soil compaction has been used intensively as a procedure for improving the strength characteristics of soils, the sensitivity of a soil is the ratio of the strength of the soil undisturbed to that of the soil after remolding. Seed and Chan (1959) have indicated that about the simplest test for revealing a sensitive structure is to compare the undrained stress-strain characteristics of an undisturbed soil sample with those of a sample remolded wet-of-optimum (Mitchell, 1964). Because, in the case of a soil liner, the permeability is the property to be considered and since soil flow properties have to be at least as much structure sensitive as strength properties are, the permeability rather than the strength has to be determined on undisturbed and remolded samples. Static and kneading compaction procedures should be used in parallel to evaluate the effect of void ratio and to concentrate the eventual effect that a particular structure might have on permeabilty.

The following conclusions should be observed when clayey soils are compacted to produce the lowest possible permeability:

a. The lowest permeabilities correspond, as a general rule, to the condition when the soil is compacted wet-of-optimum moisture.

b. The sensitivity of a soil-clay-tactoid structure is ascertained by increasing the available water and an available compactive effort and measuring the decrease in permeability. The testing program should reveal the relative significance of these two factors and lead to the optimization of field compaction; the investigation should identify the relative effects upon permeability of structural versus density changes when the soil is being compacted.

c. Compactive implements which promote shear deformation of soil will generate a better oriented structure and consequently help obtain a soil blanket with a low permeability (K).

d. The higher the moisture content during compaction, the more critically important is the density obtained, e.g. a small decrease in density (1%) may result in an increase in permeability by one order of magnitude.

3.3 Admixed Liners

3.3.1 Introduction

A variety of admixed or formed-in-place liners have been used in the impoundment of water. The linings include asphalt, concrete, soil cement, and soil asphalt, all of which are hard-surface materials. There has been a limited amount of experience in the use of some of the admixes in the lining of sanitary landiflls and the lining of impoundments of brine. They are also undergoing exposure testing in two EPA research projects (Haxo and White, 1976; Haxo et al., 1977). In this section the following types of admixes are discussed: hydraulic asphalt concrete, soil cement, and soil asphalt. Also included is a discussion on the use of prefabricated asphalt panels for lining water reservoirs. Bentonite clay, which can be considered as an admixed material, was discussed in Section 3.2.

3.3.2 Hydraulic Asphalt Concrete (HAC) and Asphalt Panels

Hydraulic asphalt concretes, used as liners for hydraulic structures and waste disposal sites, are controlled hot mixtures of asphalt cement and high quality mineral aggregate, compacted into a uniform dense mass. They are similar to highway paving asphalt concrete but have a higher percentage of mineral fillers and a higher percentage (usually 6.5 - 9.5) of asphalt cement. The asphalt used in hydraulic asphalt cement is usually a hard grade, such as 40-50 or 60-70 penetration grade. These harder asphalts are better suited as liners than softer paving asphalt.

Hydraulic asphalt concrete can be compacted to have a permeability coefficient less than 1×10^{-7} cm s^{-1}. It is resistant to the destructive wave action of water, growth of plants, and effects of weather extremes (temperature). Such asphalt concrete is stable on side slopes, resisting slip and creep, and retains enough flexibility to conform to slight deformations of the subgrade and avoid rupture from low level seismic activity. The hydraulic mix for asphalt concrete is designed with a properly graded aggregate, and high mineral filler and asphalt cement contents (Asphalt Institute, 1976).

Asphalt concrete liners may be placed with conventional paving equipment and compacted to the required thickness (Asphalt Institute, 1966).

Styron and Fry (1977) used 11 percent asphalt in a two-inch asphalt concrete liner to obtain the necessary permeability. Haxo and White (1976) used a nine percent asphalt concrete, but after one year of exposure to leachate from a simulated landfill, determined that due to potential inhomogeneities in the admixed materials resulting from inadequate mixing or compaction, a liner thickness greater than four inches may be necessary to contain wastes (Table 3-3). The HAC liner examined after 56 months of exposure was in good condition; properties had changed very little since the first specimen was examined at one year of exposure. A study by Southern California Edison showed that an optimal compacted thickness, for a pond holding primarily water, was two layers of two inches each for a total thickness of four inches (Hinkle, 1976).

The quality of the finished liner depends on the compaction during placement (Bureau of Reclamation, 1963, p 40). The liner should be compacted to least 97% of the density obtained by the Marshall Method (Asphalt Institute, 1976) or less than 4% voids (Asphalt Institute, 1974). Hinkle (1976) found that a voids content less than 2.5% produced a permeability of less than 0.001 ft/yr (1×10^{-9} cm s^{-1}), as shown in Table 3-4. Samples containing 8.5% asphalt at 97% compaction, in a pressurized permeameter, showed no observable flow (Hinkle, 1976).

Before placement of the liner, the subgrade should be properly prepared. It should not have side slopes greater than 2:1 and preferably no greater than 3:1 (Asphalt Institute, 1966). The soil should be treated with a soil sterilant to prevent puncture of the liner by weeds and roots (Asphalt Institute, 1966). Mixtures of sodium chlorate and borates are examples of such soil sterilants (Bureau of Reclamation, 1963).

Asphalt has been used for centuries as a water resistant material. More recent usage has shown that asphalt materials also are resistant to acids, bases, inorganic salts (to a 30% concentration) and to some organic compounds found in industrial wastes (Asphalt Institute, 1976). Asphalts are generally not resistant to organic solvents and chemicals, particularly hydrocarbons in which they are partially or wholly soluble. Consequently, asphalts are not effective liners for disposal sites containing petroleum derived wastes or petroleum solvating compounds such as oils, fats, aromatic solvents, or hydrogen halide vapors. Asphalt does show good resistance to inorganic chemicals and low permeability to corrosive gases such as hydrogen sulfide and sulfur dioxide.

The choice of aggregate can also be a major factor in the design of a hydraulic asphalt mix for use as a liner to confine wastes. The aggregate must be compatible with the waste, e.g. aggregate containing carbonates should be avoided if wastes are acidic.

TABLE 3-3. PROPERTIES OF ADMIX LINERS MOUNTED AS BARRIERS[a]

Admix material	Asphalt concrete[b]	Hydraulic asphalt concrete[c]	Soil cement[d]	Soil asphalt[e]	Bituminous seal[f]	Fabric + asphalt emulsion[g]
Cell No.	7,13	8,14	9,15	10,16	11,17	12,18
Particle size distribution of aggregate						
Passing 4 mesh, %	90.7	89.4	88.9	79.2	-----	-----
Passing 8 mesh, %	61.0	67.1	70.8	55.8	-----	-----
Passing 16 mesh, %	45.1	50.9	53.7	39.9	-----	-----
Passing 30 mesh, %	30.1	33.7	38.8	27.3	-----	-----
Passing 50 mesh, %	19.4	21.5	29.2	18.5	-----	-----
Passing 100 mesh, %	11.2	12.4	20.8	13.4	-----	-----
Passing 200 mesh, %	6.6	7.2	15.0	11.4	-----	-----
Soil tests						
Sand equivalent	----	----	27	31	-----	-----
Liquid limit	----	----	17.6	17.0	-----	-----
Plastic limit	----	----	non-plastic	non-plastic	-----	-----
Plasticity index	----	----	non-plastic	non-plastic	-----	-----
Asphalt tests						
Penetration at 25°C	68	68	----	-----	-----	-----
Penetration (extracted) asphalt	44	62	----	-----	-----	-----
Softening point °C (°F)	----	----	----	-----	89 (192)	-----
Viscosity, capillary at 60°C, cSt	----	----	----	1101	-----	-----
Viscosity, sliding plate at 25°C, at 0.05 sec^{-1}, MP	14.5	9.7	----	0.20	8.5	4.5
Viscosity, sliding plate at 25°C, at 0.001 sec^{-1}, MP	20.0	14.5	----	0.14	19.3	6.0
Microductility at 25°C, mm	40	76	----	7	2	29
Tests on barrier specimens						
Thickness of barrier, inch	2.2	2.4	4.5	4	0.3	0.3
Density, $g./cm^3$	2.387	2.416	2.169	2.228	-----	-----
Density, lb/ft^3	149.0	150.8	135.4(dry)	139.1	-----	-----
Void ratio (vol. voids/vol. solids), %	6.4	2.9	----	10.4	0	-----
Water swell, mil	1	0	0	17	-----	-----
Coefficient of permeability, cm/sec	1.2×10^{-8}	3.3×10^{-9}	1.5×10^{-6}[h]	1.7×10^{-3}	$<10^{-9}$	$<10^{-9}$
Compressive strength, psi	2805	2712	1910	1218	-----	-----
Compressive strength after 24 h immersion[i]	2230	2328	1323	184	-----	-----
% strength retained	80	86	69	15	-----	-----

[a] Haxo and White, 1976.
[b] Composition: 7.1 asphalt:100 aggregate.
[c] Composition: 9.0 asphalt:100 aggregate.
[d] Composition: 95 soil:5 Kaolin clay:10 type 5 cement:8.8 water.
[e] Composition: 7.0 SC-800 liquid asphalt:100 aggregate.
[f] Composition: Catalytically blown asphalt layer 4.7 kg/m² (8.7 pounds per square yard).
[g] Composition: Asphalt from emulsion spread on polypropylene nonwoven fabric - 4.8 kg/m² (8.9 lb. per square yard).
[h] Measured on molded specimen.
[i] Asphalt cement and hydraulic asphalt cement immersed in water at 60°C; soil asphalt and soil cement at room temperature.

----No Data

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TABLE 3-4. PERMEABILITY OF ASPHALT CONCRETE TO WATER[a]

Asphalt, %	Compaction,[b] %	Voids, %	Specific gravity	Unit weight	Maximum specific gravity	Permeability constant, millidarcys	Coefficient of permeability	
							cm/sec	ft/yr
7.5	99.2	2.8	2.248	140.3	2.313	7.6×10^{-7}	7.9×10^{-7}	0.82
7.5	98.0	3.9	2.223	138.7	2.313	1.6×10^{-7}	1.7×10^{-7}	0.18
7.5	93.8	8.0	2.128	132.8	2.313	1.05×10^{-4}	1.09×10^{-4}	112
7.5	91.4	10.4	2.072	129.1	2.313	1.53×10^{-3}	1.58×10^{-3}	1630
7.75	96.0	6.9	2.147	134.0	2.306	1.97×10^{-6}	2.04×10^{-6}	2.1
7.75	99.0	2.9	2.240	139.8	2.306	9.7×10^{-7}	1.0×10^{-6}	1.0
8.0	93.2	8.0	2.115	132.0	2.299	1.3×10^{-4}	1.31×10^{-4}	136
8.0	93.0	8.4	2.107	131.5	2.299	1.3×10^{-3}	1.3×10^{-3}	1340
8.0	98.7	2.6	2.240	139.8	2.299	$<1.9 \times 10^{-9}$	$<2 \times 10^{-9}$	<0.002
8.5	90.6	9.5	2.067	129.0	2.285	3.0×10^{-7}	3.1×10^{-7}	0.32
8.5	94.4	6.0	2.147	134.0	2.285	5.2×10^{-8}	5.4×10^{-8}	0.056
8.5	94.0	6.2	2.144	133.8	2.285	4.3×10^{-5}	4.4×10^{-5}	46
8.5	96.0	4.2	2.189	136.6	2.285	1.3×10^{-5}	1.4×10^{-5}	14
8.5	96.0	4.2	2.189	136.6	2.285	8.2×10^{-6}	8.48×10^{-6}	8.8
8.5	97.0	3.2	2.313	138.0	2.285	$<4.8 \times 10^{-9}$	$<5 \times 10^{-9}$	<0.005
8.5	98.0	2.1	2.236	139.5	2.285	$<3.8 \times 10^{-9}$	$<4 \times 10^{-9}$	<0.004
8.5	98.0	2.6	2.224	138.8	2.285	$<5.5 \times 10^{-10}$	$<5.7 \times 10^{-10}$	<0.0005[c]
8.75	99.0	2.3	2.226	138.9	2.279	$<1.6 \times 10^{-9}$	$<1.88 \times 10^{-9}$	<0.0016[c]
8.75	99.8	1.7	2.240	139.8	2.279	$<9.6 \times 10^{-10}$	$<9.28 \times 10^{-10}$	<0.0009[c]
8.75	99.5	2.0	2.232	139.3	2.279	$<8.0 \times 10^{-10}$	$<7.79 \times 10^{-10}$	<0.0007[c]
8.75	98.0	3.6	2.197	137.1	2.279	$<1.2 \times 10^{-9}$	$<1.21 \times 10^{-9}$	<0.001[c]

[a] Hinkle, 1976.

[b] Based upon 35 blows Marshall = 100%.

[c] Samples still on permeability apparatus at time of this writing.

Prefabricated asphalt panels have been used as liners for water reservoirs. These panels typically consist of a core layer of blown asphalt blended with mineral fillers and reinforcing fibers. The asphalt mix is molded under heat and pressure, then placed between fabric sheets with a protective coating of hot applied asphalt. The fabric sheets are usually asphalt impregnated felt, plastics, or flexible glass fabrics. Panels are one-eighth to one-half inch thick, three to four feet wide, and 10 to 20 feet long (Asphalt Institute, 1976, p. 21). The panels are rugged and flexible. They are flexible enough to conform to and mold around irregularities in the subgrade, although bends with a radius of less than 12 inches should be avoided. They are tough enough to withstand abuse from pocket knives, razor blades, animal traffic, burrowing and digging rodents, light vehicular traffic, and the erosive forces of wind and waves. When properly installed and seamed, the panels form a relatively smooth watertight seal exhibiting the resistance characteristic of asphalt as described previously. Some problems occur with aging in hot dry climates; volatile fractions are lost, causing the panels to become somewhat brittle and to shrink. Thermal expansion and contraction of exposed panels may cause "neck down" at joints, resulting in cracks and possible leaks. These problems may be partially overcome by covering the portions exposed to direct sunlight (Asphalt Institute, 1976). The panels may be joined by lapping joints or butting together and seaming by use of batten strips. Hot asphalt, cold asphalt mastic, or heat welding may be used in seaming.

3.3.3 Soil Cement

Soil cement is a compacted mixture of portland cement, water, and selected in-place soils. The result is a low strength portland cement concrete with greater stability than natural soil. The permeability of this mixture varies with the type of soil; a more granular soil produces a more permeable soil cement. A fine-grained soil produces a soil cement with a permeability coefficient of about 10^{-6} cm s^{-1} (Stewart, 1978). To date, there have been few studies performed to design a soil cement with very low permeabilities (less than 10^{-8} cm s^{-1}), as opposed to mixes designed for high compressive strength. To reduce permeability of soil cement, coatings such as epoxy asphalt and epoxy coal-tar have been used.

Any soil, except organic soil, with less than 50% silt and clay is suitable for soil cement. However, a well-graded soil with a maximum size of 0.75 inch and a maximum silt and clay content of 35% is preferable (Bureau of Reclamation, 1963). A high clay content impairs the ability to form a homogeneous cemented material thus reducing the efficiency of producing an impermeable layer. Three criteria must be considered for soil cement liners: cement content, moisture content, and the degree of compaction. The optimum moisture and cement contents are determined by laboratory testing. The optimum moisture is that which results in maximum density of the compacted soil cement. Laboratory samples should be tested in wet-dry and freeze-thaw cycle tests (ASTM D559 and ASTM D560) to determine the optimum cement content.

The aging and weathering characteristics of soil cements are good, especially those associated with wet-dry, freeze-thaw cycles. Some degradation has been noted when this substance is exposed to highly acidic environments (Stewart, 1978), but soil cements can resist moderate amounts of alkali, organic matter, and inorganic salts. One of the main deficiencies of soil cement as a liner material is its tendency to crack and shrink on drying.

3.3.4 Soil Asphalt

Soil asphalt is a mixture of available on-site soil, usually low plasticity, and liquid asphalt. A silty, gravelly soil with 10-25% silty fines is the preferred soil type. The permeability of soil asphalt after compaction varies with the percent compaction and the percent asphalt. A high void content (3-10%) soil asphalt has a measurable permeability. Soil asphalts containing cutback asphalt are not recommended as lining materials. Soil asphalt made with asphalt emulsion is not sufficiently impermeable and requires a waterproof seal such as a hydrocarbon resistant or bituminous seal (Asphalt Institute, 1976).

3.4 Flexible Polymeric Membranes

3.4.1 Introduction

Prefabricated liners based upon sheeting of polymeric materials are of particular interest for the lining of waste storage and disposal impoundments. As a group, these materials exhibit extremely low permeability. They have found substantial use in water impoundments in reservoirs and are being used in the lining of sanitary landfills and various waste disposal facilities.

Liner technology is relatively new and a wide variety of liner materials are being manufactured and marketed. These materials vary considerably in physical and chemical properties, methods of installation, costs and interaction with various wastes. Not only are there variations in the polymers used, but also there is considerable variation in the lining materials of a given polymer type due to compounding, construction, and manufacturing differences among the producers.

In this section, the lining industry, the various polymeric materials, and the liner construction and methods of manufacture are described and discussed.

3.4.2 Description of the Polymeric Liner Industry

Although it is only a small part of the plastic and synthetic rubber industry, the polymer liner industry has a unique hierarchy which needs to be examined carefully (Figure 3-4). Basically, the industry breaks down into four major segments:

- Raw materials producers
- Manufacturers of sheeting or roll goods
- Fabricators of prefabricated panels
- Installers or construction contractors.

A given company in the industry can perform two or more of these functions, e.g. a sheeting manufacturer might also fabricate and install; however, that is not the usual case. Another important factor is that of the design of the disposal site and the selection of the lining. This function is usually

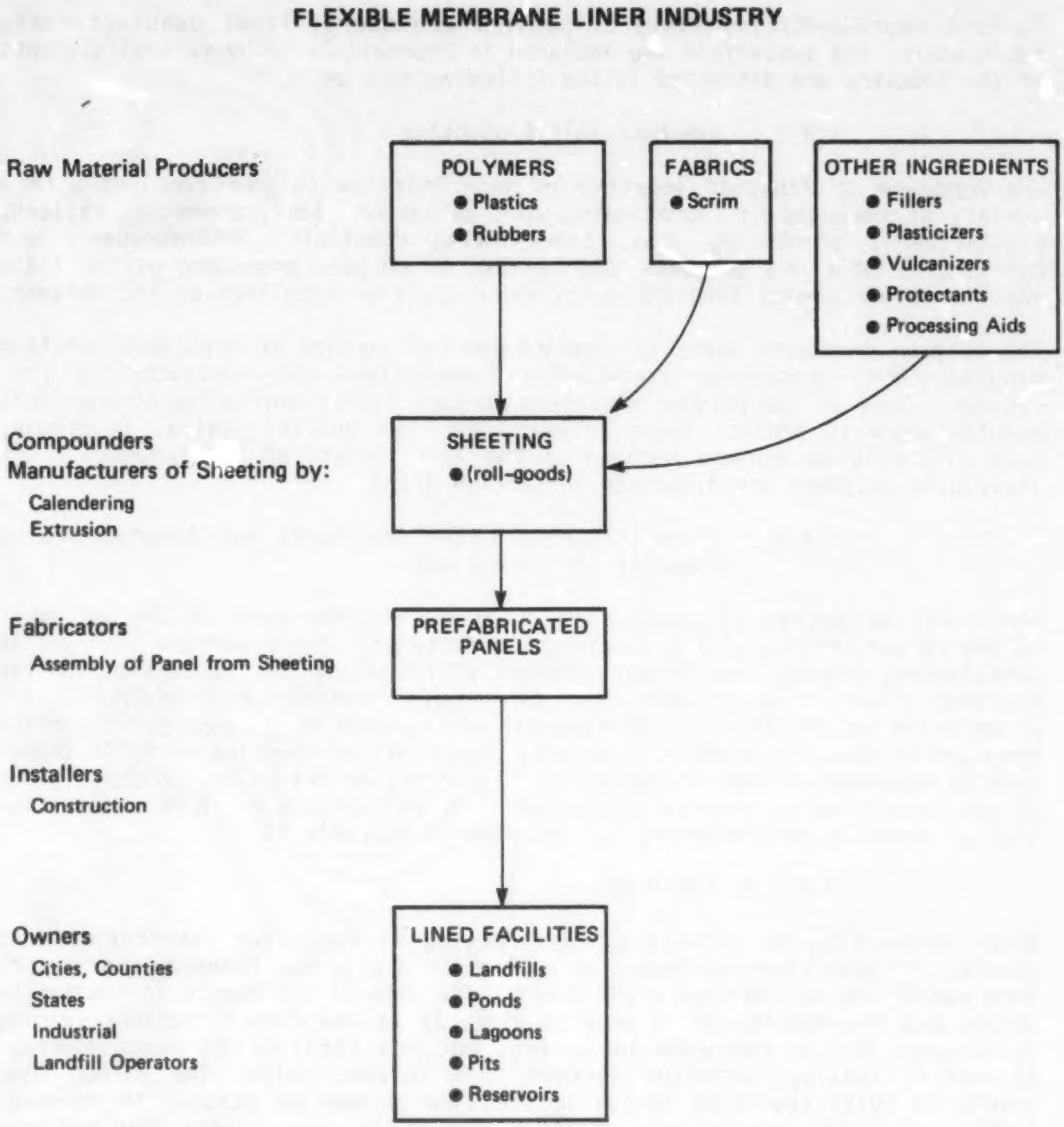

FLEXIBLE MEMBRANE LINER INDUSTRY
Raw Material Producers
POLYMERS
● Plastics
● Rubbers
FABRICS
● Scrim
OTHER INGREDIENTS
● Fillers
● Plasticizers
● Vulcanizers
● Protectants
● Processing Aids
Compounders
Manufacturers of Sheeting by:
Calendering
Extrusion
SHEETING
● (roll-goods)
Fabricators
Assembly of Panel from Sheeting
PREFABRICATED PANELS
Installers
Construction
Owners
Cities, Counties
States
Industrial
Landfill Operators
LINED FACILITIES
● Landfills
● Ponds
● Lagoons
● Pits
● Reservoirs

Figure 3-4. Basic structure of the polymeric membrane liner industry from raw material manufacturers to liner installers. A representative list of organizations and personnel in the individual segments of the industry is presented in Appendix II.

performed by engineering and consulting firms and at times by fabricators and installers.

Current representative lists of polymer producers, liner manufacturers, fabricators, and installers are included in Appendix II. The various segments of the industry are discussed in the following sections.

3.4.2.1 Raw Materials Production

The membrane or finished sheeting is made from raw polymer combined with a variety of compounding ingredients, such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, antidegradants and biocides. Table 3-5 presents such a list of polymer producers giving trade names or other common identification and respective suppliers of the polymer.

The polymer producers normally supply technical service to reputable sheeting manufacturers, presenting recommended formulations and manufacturing procedures. Some of the polymer producers conduct random monitoring of the sheet manufacturers to protect their polymer, but such quality control is growing more difficult to achieve because of the rapid growth of the industry. The individual polymers are discussed in Section 3.4.3.

3.4.2.2 Preparation of Liner Compounds and Manufacture of Sheeting and Roll Goods

The final selection of compounding ingredients for each of the polymers is the responsibility of the sheeting manufacturer. The expertise employed in formulating, mixing, and forming sheets will control the properties of the finished liner. The polymer and its required compounding ingredients are often mixed on a mill or in an internal mixer, such as a banbury. The mixed compound is then converted continuously into rolls of sheeting 48 to 96 inches wide by hundreds of feet in length by calendering or extrusion. A description of the manufacturing process is presented in Section 3.4.4. A representative list of sheeting manufacturers is presented in Appendix II.

3.4.2.3 Fabrication

After calendering or extrusion, the sheeting is ready for fabrication into panels. In this step the sheets or roll goods are joined (seamed) together to form panels (up to 100 feet x 200 feet). The size of the panels is limited by weight and the ability of a crew to place it in the field. Various seaming techniques can be employed including, but not limited to: heat seaming, dielectric seaming, adhesive systems, and solvent welds. The method used should be fully specified including the type of quality control to be used. Factory seams are usually more reliable than field seams, since they are made under carefully controlled conditions. If the area to be lined is small enough, the entire finished liner may be prefabricated in one piece, eliminating field seaming altogether; this is called a drop-in liner.

TABLE 3-5. POLYMER PRODUCERS AND SUPPLIERS

Polymer	Trade Name	Company
Butyl rubber	-	Exxon Columbian Carbon Polysar
Chlorinated polyethylene (CPE)	CPE[a]	Dow Chemical
Chlorosulfonated polyethylene (CSPE)	Hypalon	Du Pont
Elasticized polyolefin	3111	Du Pont
Epichlorohydrin rubbers	Herclor	Hercules
	Hydrin	B. F. Goodrich
Ethylene propylene rubber (EPDM)	Epcar	B. F. Goodrich
	Epsyn	Copolymer
	Nordel	DuPont
	Royalene	Uniroyal
	Vistalon	Exxon
Fluorocarbon polymers	Viton/Teflon	Du Pont
Neoprene (chloroprene rubber)	Neoprene[a]	Du Pont Denka
Nitrile rubber (NBR)	Chemigum	Goodyear
	Hycar	B. F. Goodrich
	Krynac	Polysar
	NYsyn	Copolymer
	Paracril	Uniroyal
Polybutylene (PB)	-	Shell Chemical
Polyester	Hytrel	Du Pont
Polyethylene - HDPE	-	Many
- LDPE	-	Many
Polyvinyl chloride	PVC[a]	Borden General Tire B.F. Goodrich Firestone Pantasote Stauffer Tenneco Union Carbide
Thermoplastic elastomer	Santoprene	Monsanto
	TPR	Uniroyal
Urethane	-	Many

---

[a] Generic name

3.4.2.4 Installation

After the raw materials are produced, compounded, converted into roll-goods and fabricated into panels, the installation is the final step in completing the liner project. The installation should be performed by an experienced liner installer or by a qualified specialty contractor whose experience is in liner installation, the associated earthwork, and piping installation. The installation is not complete until all field seams have been inspected to the satisfaction of the end user or his representative. Air lancing and ultrasonic methods have been used in the field to make 100% inspection of seams.

3.4.2.5. Engineering and Design Services

Another important segment of the liner industry is the engineering and design services that are furnished by various engineering and consulting firms. Such services can supply the designs of disposal sites and participate in the selection of the liner systems to be used. They also can supply quality control services during the installation of the liners.

3.4.2.6. Integration in the Liner Industry

Some companies perform two or more functions within the industry. For example, some manufacturers of sheeting will also fabricate. Some installers fabricate, other installers will design and supply engineering services.

3.4.3 Polymers Used in Liner Manufacture

Polymers used in the manufacture of lining materials are listed in Table 3-6. They include rubbers and plastics differing in polarity, chemical resistance, basic composition, etc. They can be classified into four types:

- Rubbers (elastomers) which are generally vulcanized.
- Plastics which are generally unvulcanized, such as PVC.
- Plastics which have a relatively high crystalline content, such as the polyolefins.
- Thermoplastic elastomers which do not need to be vulcanized.

Table 3-6 lists the various types of polymers that are used and indicates whether they are used in the vulcanized or nonvulcanized form and whether they are reinforced with fabric. The polymeric materials most frequently used in liners are polyvinyl chloride (PVC), chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), butyl rubber, ethylene propylene rubber (EPDM), neoprene, high-density polyethylene (HDPE), and low-density polyethylene (LDPE). The thickness of polymeric membrane for liners range from 20 to 120 mils, with most in the 20-60 mil range.

Most of the lining materials are based on individual polymers; however, plastics and rubber technology has been developing blends or rubber-plastic alloys for improved properties. Consequently, it is difficult to make generic classifications based on individual polymers of the liners though one polymer may predominate in the compound. Blending of polymers introduces the long range possibility of performance specifications being needed. However,

Table 3-6 POLYMERIC MATERIALS USED IN LINERS

Polymer	Use in liners		Fabric reinforcement	
	Thermoplastic	Vulcanized	With	W/O
Butyl rubber	No	Yes	Yes	Yes
Chorinated polyethylene	Yes	Yes	Yes	Yes
Chlorosulfonated polyethylene	Yes	Yes	Yes	Yes
Elasticized polyolefin	Yes	---	No	Yes
Elasticized polyvinyl chloride	Yes	---	Yes	No
Epichlorohydrin rubber	Yes	Yes	Yes	Yes
Ethylene propylene rubber	Yes	Yes	Yes	Yes
Neoprene (chloroprene rubber)	No	Yes	Yes	Yes
Nitrile rubber	Yes	---	Yes	---
Polyethylene	Yes	No	No	Yes
Polyvinyl chloride	Yes	No	Yes	Yes

liner performance in the field cannot, at the present time, be defined by laboratory tests.

Most of the membrane liners currently manufactured are based on unvulcanized or uncrosslinked polymeric compounds which are thus thermoplastic. Even if the polymer in the vulcanized form is more chemically resistant, such as CPE and CSPE, it is generally supplied unvulcanized because it is easier to obtain reliable seams and to make repairs in the field. Thermoplastic polymers can be heat sealed or can be seamed with solvent or bodied solvent (a solvent containing dissolved polymer to increase the viscosity and reduce the rate of evaporation). Information on individual polymers and liners is presented in subsequent subsections. Subjects covered on each polymer are: composition, general properties and characteristics, general use, and specific use in liners.

3.4.3.1 Butyl Rubber

Liners of butyl rubber were among the first synthetic liners to be used for potable water impoundment and have been in this type of service for about 30 years (Smith, 1980).

Butyl rubber is a copolymer of isobutylene (97%) with small amounts of isoprene introduced to furnish sites for vulcanization (Morton, 1973, pp. 249-59). The important properties of butyl rubber to its use as a liner are:

a. low gas and water vapor permeability
b. thermal stability
c. ozone and weathering resistance
d. chemical and moisture resistance
e. resistance to animal and vegetable oils and fats.

It is generally compounded with fillers and some oil and vulcanized with sulfur. Butyl vulcanizates are highly swollen by hydrocarbon solvents and petroleum oils, but are only slightly affected by oxygenated solvents and other polar liquids. Butyl also has a high resistance to mineral acids. After 13 weeks of immersion in 70% sulfuric acid, a butyl compound showed little loss in tensile strength or elongation (Morton, 1973, pp. 249-59). Butyl rubber has a high tolerance for extremes in temperature and retains its flexibility throughout its service life. It has good tensile strength and desirable elongation qualities.

Butyl rubber liners are manufactured in both reinforced and in unreinforced versions. They are difficult to seam and to repair. They require special room temperature vulcanizing adhesives (Kumar and Jedlicka, 1973; Lee, 1974).

3.4.3.2 Chlorinated Polyethylene

Chlorinated polyethylene (CPE) is produced by a chemical reaction between chlorine and high-density polyethylene. Presently available polymers contain 25-45% chlorine and 0-25% crystallinity. CPE is compounded and used in thermoplastic and crosslinked compositions.

Since CPE is a completely saturated polymer (no double bonds) it is not susceptible to ozone attack and weathers well. The polymer also has good tensile and elongation strength. Chlorinated polyethylene is characterized by resistance to deterioration by many corrosive and toxic chemicals. Because they contain little or no plasticizer, CPE liners have good resistance to growth of mold, mildew, fungus, and bacteria. Membranes of CPE can also be formulated to withstand intermittent contact with aliphatic hydrocarbons and oils. CPE will swell in the presence of high concentrations of aromatic hydrocarbons and oils but regains some of its original properties when removed from that environment. Continuous exposure to aromatics will shorten the service life of the liner. In most cases CPE liners are not recommended for containment of aromatic liquids (Dow, 1977).

CPE can be compounded with other polymers, making it a feasible base material for a broad spectrum of liners. CPE can be alloyed with PVC, PE and numerous synthetic rubbers. Nevertheless, at least half the polymer content of CPE liners is CPE resin. CPE is widely used to improve the stress crack resistance and softness of ethylene polymers and to improve the cold crack resistance of flexible polyvinyl chloride. CPE membranes are available in varied thicknesses in unreinforced or fabric reinforced versions (Bureau of Reclamation, 1963, p. 23). Membranes of CPE are generally unvulcanized and thus can be seamed by bodied-solvent adhesives, solvent welding or dielectric heat sealing (Stewart, 1978).

3.4.3.3 Chlorosulfonated Polyethylene (CSPE)

Chlorosulfonated polyethylene is a family of polymers prepared by reacting polyethylene in solution with chlorine and with sulfur dioxide. Presently available polymers contain from 25-43% chlorine and from 1.0-1.4% sulfur. They can be used in both thermoplastic (uncrosslinked) and in vulcanized (crosslinked) compositions. Uncured CSPE is more thermoplastic than other commonly used elastomers. It is generally tougher at room temperature, but softens more rapidly as temperatures are increased (Morton, 1973, pp. 337-8).

Chlorosulfonated polyethylene (CSPE) is characterized by ozone resistance, light stability, heat resistance, good weatherability, and resistance to deterioration by corrosive chemicals, e.g. acid and alkalies. It has good resistance to growth of mold, mildew, fungus, and bacteria. Membranes of this material are available in both vulcanized and thermoplastic forms, but primarily in the latter. Usually, they are reinforced with a polyester or nylon scrim and generally contain at least 45% of CSPE polymer. The fabric reinforcement gives needed tear strength to the sheeting for use on slopes, and reduces the distortion resulting from shrinkage when placed on the base and when exposed to the heat of the sun.

CSPE can be seamed by heat sealing, dielectric heat sealing, solvent welding, or by using "bodied" solvent adhesive. Membranes of this polymer do not crack or fail at extremes of temperatures or from weathering. Disadvantages of CSPE membranes are low tensile strength, a tendency to shrink from exposure to sunlight (Clark and Moyer, 1974, p. 20), and relatively poor resistance to oils. Also, some CSPE tends to harden on aging, due to crosslinking by moisture, ultraviolet radiation, and heat.

Membranes of CSPE are also available in colors other than black, without appreciable loss of other desirable characteristics (Du Pont, 1979).

3.4.3.4 Elasticized Polyolefins

Elasticized polyolefin is a blend of rubbery and crystalline polyolefins. This polymeric material was introduced in 1975 as a black unvulcanized, thermoplastic liner, which readily and easily heat sealed with a specially designed heat welder in the field or at the factory. It has a low density (0.92) and is highly resistant to weathering, alkalis, and acids (Haxo and White, 1977). This membrane is unsupported and is manufactured by blow extrusion and supplied in sheets 20 mil thick, 20 feet wide, and up to 200 feet long (Du Pont, 1979) which are shipped to site for assembly in the field.

Some difficulties have been encountered with elasticized polyolefin in low temperature and high winds, in oily environments, and in adhesion to structures.

3.4.3.5 Epichlorohydrin Rubbers (CO and ECO)

Included in this classification are two epichlorohydrin-based elastomers which are saturated, high molecular weight, aliphatic polyethers with chloromethyl side chains. The two types include a homopolymer and a copolymer of epichlorohydrin and ethylene oxide. These materials are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group, including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

Epichlorohydrin elastomer vulcanizates exhibit the following characteristics:

a. resistance to hydrocarbon solvents, fuels and oils.
b. ozone and weathering resistance.
c. low rate of gas/vapor permeability.
d. thermal stability.
e. good tensile and tear strength.

Epichlorohydrin rubber has a high tolerance for temperature extremes and retains its flexibility at extreme temperatures throughout its service life. The homopolymer has a performance range of 0 to 325°F. The copolymer shows improved low temperature flexibility and is recommended for service from -40 to 300°F.

Epichlorohydrin elastomers can be seamed with room temperature vulcanizing adhesives.

3.4.3.6 Ethylene Propylene Rubber (EPDM)

Ethylene propylene rubbers are a family of terpolymers of ethylene, propylene, and a minor amount of nonconjugated diene hydrocarbon. The diene supplies double bonds to the saturated polymer chain to be chemically active sites for vulcanization, usually with sulfur. These rubbers vary in ethylene:propylene ratio, in the type and amount of the third monomer, and in molecular weight. Although EPDM liners are generally based on vulcanized compounds, thermoplastic EPDM liners are also available. Both versions are manufactured as fabric reinforced and unsupported sheeting.

Liners based on vulcanized EPDM compounds have excellent resistance to weather and ultraviolet exposure and, when compounded properly, resist abrasion and tear. Because of its excellent ozone resistance, minor amounts of EPDM are sometimes added to butyl to improve the weather resistance of the latter. EPDM liners tolerate extremes of temperature, and maintain their flexibility at low temperatures. They are resistant to dilute concentrations (10% by weight) of acids, alkalis, silicates, phosphates, and brine, but are not recommended for petroleum solvents (hydrocarbons) or for aromatic or halogenated solvents.

Vulcanized EPDM membranes require the use of special cements and careful application to assure satisfactory field seaming. The proposed seam construction should be tested in the use environment to assure serviceability. Thermoplastic EPDM liners are seamed by thermal methods.

3.4.3.7 Neoprene

Neoprene is the generic name of synthetic rubbers based upon chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in mechanical properties, e.g. flexibility and strength. However, neoprene is superior to natural rubber in its resistance to oils, weathering, ozone, and ultraviolet radiation. Neoprene is resistant to puncture, abrasion, and mechanical damage. Neoprene membranes have been used primarily for the containment of wastewater and other liquids containing traces of hydrocarbons. They also give satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term performance (Kumar and Jedlicka, 1973; Lee, 1974).

Neoprene sheeting for liners is vulcanized, thus vulcanizing cements and adhesives must be used for seaming.

3.4.3.8 Polyethylene

Polyethylene is a thermoplastic polymer based upon ethylene. It is made in two major types: (1) low-density polyethylene, and (2) high-density polyethylene. The properties of a polyethylene are largely dependent upon its crystallinity and density. High-density polyethylene polymers exhibit superior resistance to oils, solvents, and permeation by water vapor and gases. Unprotected clear polyethylene degrades readily on outdoor exposure, but the addition of 2-3% carbon black can produce improved ultraviolet light protection. Polyethylenes, for the most part, are free of additives such as plasticizers and fillers.

Both types of polyethylene have been used as liners. Membranes of low-density polyethylene have been used unsupported for 15 to 20 years (Hickey, 1969) in lining canals and ponds. Recently, high-density polyethylene in heavy sheeting has been introduced. The low-density polyethylene (LDPE) available in thin sheeting tends to be difficult to handle and to field seam. Also, it is punctured easily under impact such as when rocks are dropped on the lining; however, it has good service puncture resistance as a buried membrane lining. Linings of high-density polyethylene (HDPE) recently introduced are available in thick sheets up to 125 mil; special seaming equipment has been developed for making seams both in the factory and in the field. This type of liner is very stiff compared to most of the other membranes described.

3.4.3.9 Polyvinyl Chloride

Polyvinyl chloride is produced by any of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic polymer which is compounded with plasticizers and other modifiers to produce a wide range of physical properties.

PVC liners are produced in roll form in various widths and thicknesses. Most liners are used as unsupported sheeting, but fabric reinforcement can be incorporated. PVC compounds contain 25% to 35% of one or more plasticizers to make the sheeting flexible and rubber-like. They also contain 1% to 5% of a chemical stabilizer and various amounts of other additives. The PVC compound should not contain any water soluble ingredients. There is a wide choice of plasticizers that can be used in PVC sheeting, depending upon the application and service conditions under which the PVC compound will be used. Plasticizer loss during service is a source of PVC degradation. There are three basic mechanisms for plasticizer loss: volatilization, extraction, and microbiological attack. The use of the proper plasticizers and an effective biocide can virtually eliminate microbiological attack and minimize volatility and extraction. The PVC polymer, itself, is not affected by these conditions. It is affected, however, by ultraviolet exposure.

The principal reason for loss of plasticizer is by volatilization in the heat of the sun rather than solution in the waste fluid. Carbon black prevents ultraviolet attack but does cause the absorption of solar energy raising the temperature to a high level to cause vaporization of plasticizer. A soil or other suitable cover material used to bury the liner protects it from ultraviolet exposure and reduces the rate of plasticizer loss. PVC sheeting is not recommended for exposure to weathering and ultraviolet light conditions during its service life.

Plasticized PVC sheeting has good tensile, elongation, and puncture and abrasion resistance properties. It is readily seamed by solvent welding, adhesives, and heat and dielectric methods.

PVC membranes are the most widely used of all polymeric membranes for waste impoundments. They show good chemical resistance to many inorganic chemicals (Chan et. al. 1978, p. 19); however, they are attacked by many organic chemicals, particularly hydrocarbons, solvents, ano oils. Special compounds of PVC are available, designated as Oil-Resistant PVC (PVCOR), that possesses high resistance to oil attack. These "oil-resistant" grades of sheeting must be made with "specialty" plasticizers; the PVC polymer is inherently resistant to the effects of oils.

Polymers such as nitrile rubber, CPE and EVA may be used to replace the liquid plasticizers so that the PVC liner is not affected by the waste fluid.

3.4.3.10 Thermoplastic Elastomers (TPE)

Thermoplastic elastomers are a relatively new class of rubbery materials (Walker, 1979). They include a wide variety of polymeric compositions from highly polar materials, such as the polyester elastomers, to the nonpolar materials, such as ethylene-propylene block polymers. These polymers are thermoplastic and nonvulcanized. They are processed and shaped at relatively high temperatures at which they are plastic; when they are cooled to normal ambient temperatures, they behave like vulcanized rubbers. Products made of these polymers have a limited upper temperature service range, which, however, is substantially above the temperatures encountered in waste disposal sites.

Of particular potential interest for use in liners are the polyolefin thermoplastic elastomers such as thermoplastic EPDM, which are probably related to the elasticized polyolefins, and nitrile rubber/PVC blends for oil resistant liners. Such liner materials are now under development and test.

Nitrile/PVC thermoplastic elastomer blends have excellent oil, fuel, and water resistance with high tensile strength and excellent resistance to ozone and weathering. Blends tend to stiffen at low temperatures but remain serviceable.

As with liners of other thermoplastic polymers, liners of thermoplastic elastomers can be heat sealed to make seams and should be easy to repair; however, their durability in various chemical environments remains to be tested.

3.4.4 Membrane Manufacture

The two basic methods used in the manufacture of polymeric sheeting are calendering and extrusion. Calendering is used in forming both unsupported and fabric reinforced sheeting, whereas extrusion is only used in making unsupported sheeting.

Calendering is the more common method of forming the sheeting. In this process, heated rubber or elastic compounds are passed between the heated rolls of a calender to form a sheet of predetermined thickness. A calender usually consists of three to four rolls, as shown in Figure 3-5. The arrangement for preparing a single-ply sheeting on a 3-roll calender is shown in Figure 3-6. Unsupported sheeting is usually a single-ply construction; however, some manufacturers have resorted to multiple plying of unsupported liners to eliminate the formation of pinholes through the sheet. By manufacturing sheeting in this manner, the probability of a pinhole in one ply coinciding with a pinhole in another is remote.

Some manufacturers set up special straining operations to clean out all grit that may be in the compound. This operation immediately precedes the calendering. In this step, grit and other coarse particles are screened out to yield a clean compound for the calender.

Reinforcing fabric can be placed between the plies of the polymeric compound to produce a supported liner. In this case, sufficient material must be placed on both sides of the fabric in order that pinholes are not generated between the fabric and the outside of the sheeting. Also, there should be sufficient compound present to strike through the open weave of the fabric and achieve direct contact of the rubber on both sides of the fabric. Fabric reinforcement is usually achieved through the use of open fabrics or scrim of nylon, polyester, polypropylene, or glass fiber. The thread count or ends per inch usually range from 6 x 6 to 10 x 10 per inch, but some have run to 20 x 20. Figure 3-7 shows several types of scrim. A coating is applied to the finished scrim after weaving in order to tack the yarns in place so that the finished scrim construction pattern will not lose its shape. Different coating formulations are used, depending on the end use. Scrims or fabrics to be used with vulcanized elastomeric lining materials are usually treated with

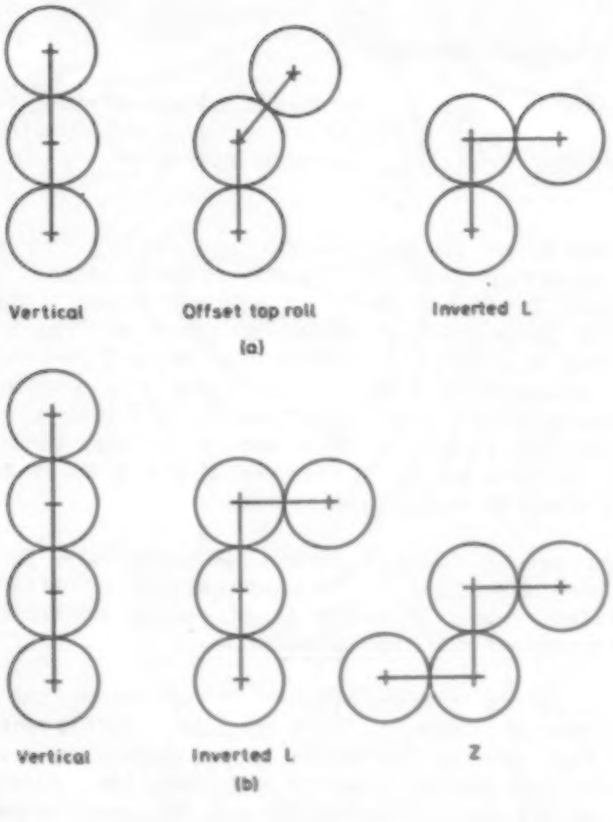

Vertical
Offset top roll
Inverted L
(a)
Vertical
Inverted L
Z
(b)

Figure 3-5. Roll configuration of calenders: (a) three-roll calenders, and (b) four-roll calenders (Blow, 1971).

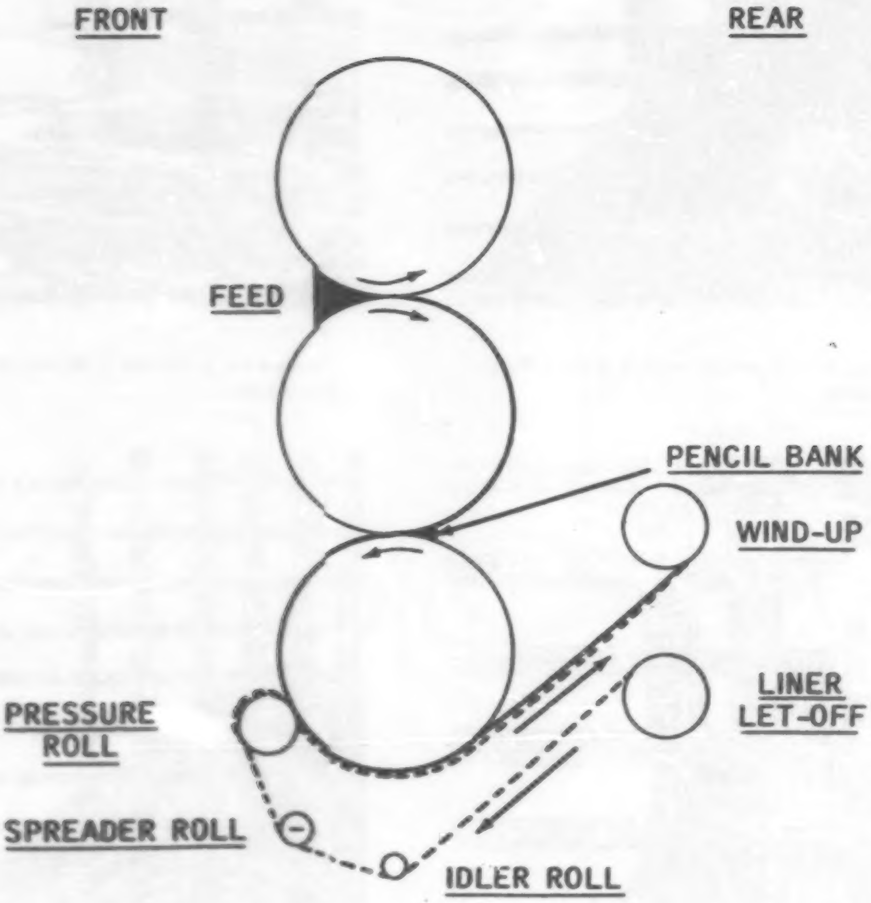
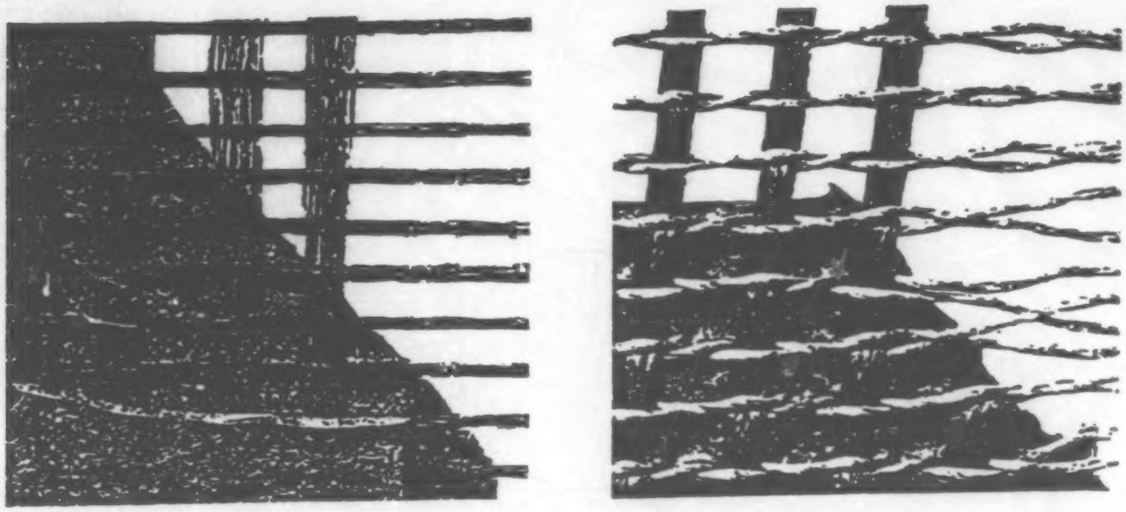
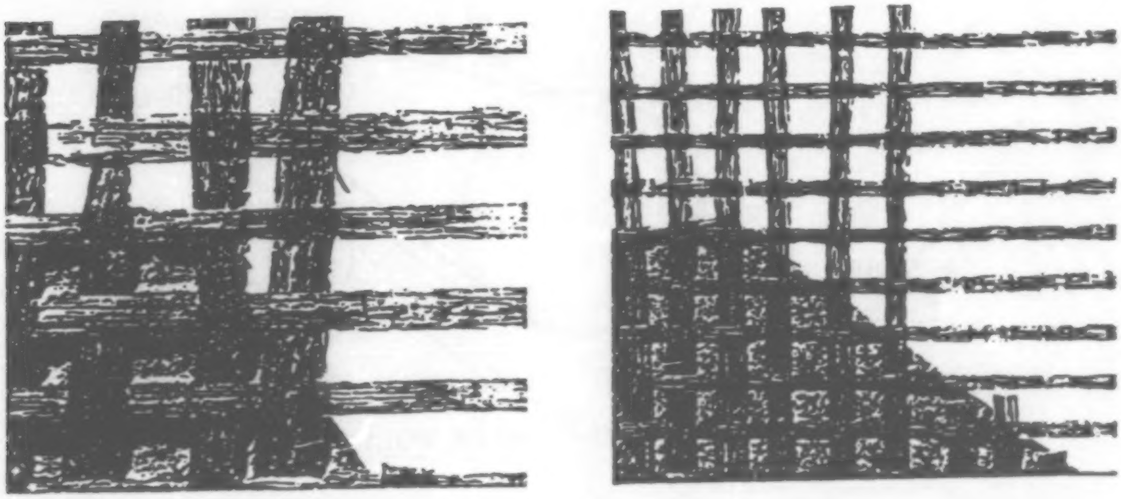

FRONT
REAR
FEED
PENCIL BANK
WIND-UP
LINER
LET-OFF
PRESSURE
ROLL
SPREADER ROLL
IDLER ROLL

Figure 3-6. Calender arrangement - sheeting, one-pass or ply-up with pencil bank (Banks, 1966).



Manufacturer F. 30 mils (0.76 mm), B-5602. Photo P222-D-65685

Manufacturer A. 60 mils (1.52 mm), B-4606. Photo PX-D-68886



Manufacturer G. 30 mils (0.76 mm), B-5540. Photo PX-D-68887

Manufacturer H. 30 mils (0.76 mm), B-5560. Photo PX-D-68888

Figure 3-7. Nylon-reinforced, butyl lining samples showing different weaves and weights of nylon used by four manufacturers (6x magnification). From Hickey, 1971.

an adhesive coating which chemically reacts with the membrane material during the curing cycle to produce adhesion to the polymer compound.

The extrusion technique is used primarily with polyolefins, such as polyethylene, and with elasticized polyolefin. For thinner films, a tube of film is produced and slit to form a sheet. For the thicker gauge polyethylenes, thick sheets are extruded directly.

3.5 Sprayed-on Linings

3.5.1 Introduction

Liners for disposal impoundments can potentially be formed in the field by spraying onto a prepared surface a liquid which then solidifies to form a continuous membrane. Such liners have been used in water control and impoundment, e.g. for canals, small reservoirs, and ponds. Most of the experience with this type of liner has been with air blown asphalt; however, a variety of new materials are becoming available which have been used in small water control installations. Sprayed-on liners are seam-free, but preparing them pinhole-free in the field poses serious difficulties. Furthermore, most of the spray-on materials that have been considered are thermoplastic and are of low molecular weight, e.g. asphalt, and may interact adversely with many wastes. Some of the new materials that are being introduced are of high molecular weight or contain polymeric additives which improve their durability.

In this section, the following materials are discussed; airblown asphalt, emulsified asphalt, urethane modified asphalt, and rubber and plastics, in either liquid or latex form.

3.5.2 Air-blown Asphalt

Membranes of catalytically-blown asphalt are the most commonly used sprayed-on linings. The asphalts used in making these membrane linings have high softening points and are manufactured by blowing air through the molten asphalt at temperatures in excess of 500°F in the presence of a catalyst such as phosphorous pentoxide or ferric chloride. To prepare the membrane, the asphalt is sprayed on a prepared soil surface at a temperature of 400°F, at a pressure of 50 psi through a slot-type nozzle, and at a rate of 1.5 gal yd^{-2} (Bureau of Reclamation, 1963, p. 80). The finished liner is usually 0.25 inch thick (Bureau of Reclamation, 1963, p. 79), formed by two or more passes of the spray device and overlapping sections by one or two feet (Clark and Moyer, 1974). It can be placed during cold or wet weather, in large quantities, by mobile equipment (Bureau of Reclamation, 1963, p. 10). Sprayed-on membranes retain their tough flexible qualities indefinitely when properly covered and protected from mechanical damage (Asphalt Institute, 1976). The actual placing of the earth covers on a sprayed-on membrane may cause some damage to its integrity.

Studies have shown the addition of 3-5% rubber improves the properties of the asphalt by inducing greater resistance to flow, increased elasticity and toughness, decreased brittleness at low temperatures, and greater resistance to aging (Chan et al., 1978, p. 17).

Bituminous seals are used on asphalt concrete, portland cement concrete, soil asphalt, or soil cement linings to close pores, thus improving waterproofing or when there may be a reaction between the stored liquid and the lining. The two types of seals usually applied are:

a. An asphalt cement sprayed over the surface about one qt yd^{-2} to form a membrane about 0.04 in. thick.

b. An asphalt mastic containing 25 - 50% asphalt cement, the rest being a mineral filler, squeegeed on at 5 - 10 lb yd^{-2}.

Installation of sprayed-on asphaltic membranes is usually done on a subgrade which has been dragged and rolled to obtain a smooth surface. If there is an excessive number of irregular rocks and angular pieces, a fine sand or soil "padding" is necessary for good membrane support (Bureau of Reclamation, 1963, p. 81). Covering protects the membrane from most mechanical damage.

A special deep penetration formula of liquid cutback asphalt was applied over natural-on-site soil at a rate of two gal yd^{-2}. The seepage rate, in this case, was reduced from 15.9 to 6.14 ft^3 ft^{-2} yr^{-1} (Day, 1970, p. 20). Another formulation of cationic asphalt, incorporating white gasoline and water, penetrated 3/16 to 3/8 inch into the soil. This proved to be inadequate for complete sealing (Bureau of Reclamation, 1963, p. 115). A special cationic asphalt emulsion forms a highly impermeable seal at the soil interface through the attraction of the positively charged asphalt droplets to the negatively charged soil particles as the emulsion penetrates the substrate. As little as 15 fluid oz ft^{-2} results in almost zero seepage. This product has been used mainly in reservoirs and ponds (Wren, 1972).

Field data on a hot asphalt membrane lining in a canal lateral was obtained after 11 years of service. The seepage rate at this time was 0.08 $ft^3/ft^2/$day. The seepage rate prior to placement of the liner was 9.9 $ft^3/ft^2/$day. Ninety percent of the aging occurred during the first four years of membrane service. A poor correlation was found between the 14-day laboratory aging test at (60°C) and actual field aging. Geier (1964, p. 3) concluded that, if properly applied and covered, a buried hot applied asphalt membrane canal lining should last beyond 12 years.

Styron and Fry (1977) used an AC-40 grade asphalt cement as a lining material in tests with two flue gas desulfurization (FGD) sludges. A base of silty sand was compacted to six inches depth and cured at 78°F and 50% humidity for two to three days. The asphalt liner was then sprayed on the base at a rate of 0.75 gal yd^{-2}. After one year, under a pressure head of five feet of water, no liquid had passed through the liner. Specifications for AC-40 require a viscosity of 4000 ± 800 poises at 140°F (60°C) and a minimum penetration of 20. This asphalt requires temperatures of 300 - 400°F for spraying (Klym and Dodd, 1974).

Except for resistance to hydrocarbon solvents, oils, and fats, the chemical resistance of asphaltic liners is, in general, good. Asphaltic membranes are resistant to methyl and ethyl alcohols, glycols, mineral acids other than nitric acid (at moderate temperatures and concentrations), mineral salts, alkalis to about 30% concentration, and corrosive gases such as H_2S and SO_2. Asphaltic liners exhibit variable to poor performance when exposed to hydrogen halide vapors, but are essentially impermeable to water (Anonymous, 1966). Preparing pinhole-free membranes on large areas by spraying techniques, particularly when hot materials must be sprayed, poses a variety of problems which are discussed in Section 5.5.

3.5.3 Membranes of Emulsified Asphalt

Emulsions of asphalt in water can be sprayed at ambient temperatures (above freezing), to form continuous membranes of asphalt after breaking of the emulsion and evaporation of the water. The membranes are less tough and have lower softening points than membranes of hot applied catalytically-blown asphalt. Toughness and dimensional stability can be achieved by spraying asphalt emulsions onto a supporting fabric. Fabrics of woven jute, woven or nonwoven glass fiber, and nonwoven synthetic fibers have been used with various anionic or cationic asphalt emulsions to form linings for ponds and canals and as reinforcing patches under asphalt concrete overlays to prevent "reflection" of cracks in the old pavement beneath. Seams in the supporting fabric are often sewn with portable sewing machines after the fabric is placed (Phillips Petroleum, 1972).

3.5.4 Urethane Modified Asphalt

A urethane modified asphalt liner system is being marketed. It is generally spray applied, but may be squeegeed onto a prepared surface. A premix is combined with the activator, and sprayed on at a rate of two gallons per minute, covering about eight square yards per minute. The final membrane is generally recommended to have a thickness of 50 mil, usually obtained by applying one coat of 0.28 gal yd^{-2} on horizontal surfaces or two coats on vertical surfaces. The second coat may be applied about 15 minutes after the first coat. The membrane must cure for 24 hours before being put into service. This system has good UV stability and low temperature ductility, eliminating the need for a soil cover in most cases. The liner system is limited to a maximum of 140°F continuous exposure and is not recommended for prolonged exposure to hydrocarbon or organic solvents. It should be applied only to properly prepared surfaces. The surface must be clean and dry. Porous surfaces should be filled. Generally, a primer and a bonding agent are applied prior to the application of the actual membrane. The procedures for several base surfaces and the necessary precautions are provided by the manufacturer (Chevron, 1980).

3.5.5 Rubber and Plastic Latexes

Rubber and resin latexes have also been studied as spray-on liners. Gulf South Research Institute studied two synthetic latexes. The first was an experimental styrene polymer, which had a 50% solids content with a high concentration of wetting agents. The spray was allowed to soak into the soil and dry. The result was a fairly resilient film with good soil sealing capabilities. The second latex was an off-grade polyvinylidene chloride. It also had a 50% solids content and was used as a vapor barrier on air strips. It formed a film on the soil surface and was reported to provide a good seal at high pressures (Wren, 1972, pp. 30-40).

3.6 Soil Sealants

The permeability of some soils can be significantly reduced by the application of various chemicals or latexes. They may be waterborne, mixed in place, spray applied, or injected below the soil surface (Bureau of Reclamation, 1973, p. 13). Water borne or spray-on polymer soil sealants can reduce permeability of earth lined impoundments. However, the sealing effect is confined to the upper few centimeters and can be significantly diminished by the effects of wet-dry and/or freeze thaw cycles. Types of sealants include resinous polymer-diesel fuel mixtures, petroleum based emulsions, powdered polymers which form gels, and monovalent cationic salts (Bureau of Reclamation, 1963, p. 115). See Table 3-7 for a list of representative soil sealants.

Soil sealants utilizing monovalent cations, mainly sodium salts, chemically reduce the effective porosity of the soil for flow by replacing the multivalent cations in the clay structure. This exchange renders the clustered soil particles more easily dispersed (Morrison, 1965, p. 1). Sodium carbonate applied at a rate of two lb yd^{-2} provided a seepage reduction of greater than 90% in Bureau of Reclamation tests. The seepage reduction was still 80% after removal of the top six inches of soil. Sodium pyrophosphate and sodium silicate are also potential soil sealants. Soil treated with sodium silicate and sulfuric acid prior to compaction showed a significant seepage reduction and is compatible with sulfuric acid bearing wastes (Clark and Moyer, 1974, p. 13).

Some powdered polymers can form gelatinous masses which tend to fill the soil voids, thus effecting a surface seal. Some early studies showed that this surface seal is easily damaged by a water spray, indicating that durability tests should be made when considering this type of liner (Morrison, 1965, p. 2). A powdered mixture of carboxymethyl cellulose and alum (0.25 CMC + 0.05% alum by wt of dry soil) was mixed with the soil and compacted to a six-inch thickness in one project. The seepage was reduced only slightly from 16 to 14 ft^3 ft^{-2} yr^{-1} (Day, 1970, p. 21). Soil sealants based on polymers are generally mixtures of swellable linear and crosslinked polymers of approximately the same molecular weight. The linear portion sorbs to the soil, forming a flexible network. The crosslinked polymer particles can flow, and thus can conform to and permeate the soil pores. The formulation depends on the application. The polymer is usually mixed in a low pH water/acid solution and sprayed onto an unfilled site as a low viscosity slurry. The low pH allows the slurry to penetrate the surface and form a deeper seal.

Polymeric soil sealants may be applied as a dry blend which is mixed into the soil and compacted, sprayed on as a slurry, or dusted on as a powder. Highway construction equipment may be used for dry blending. Water hauling trucks

TABLE 3-7. REPRESENTATIVE SOIL SEALANTS[a]

Sealant	Application	Remarks
Cationic asphalt emulsion	Farm ponds	Requires approximately 19,000L/4,047 m^2 (5,000 gal/acre) dispersed in water.
Oil soluble polymers in diesel fuel	Fresh water	Injected beneath surface of water where seepage was occurring.
Sodium tetraphosphate	Sulfite liquor storage	Dispersant distributed in 15.2-cm (6-in.) layer of soil at 2.3 kg/9 m^2 (5 lb/100 ft^2). Careful compaction rendered soil impervious.
Sodium carbonate	Canals	Wet-dry cycles disrupt water barrier. Used 183 g (0.4 lb) of reagent/0.84 m^2 (yd^2) of soil.
Lignin derivatives gelled alum	Desalination byproduct brine	1% lignin. Cost $3,400/4,047 m^2 (acre).
Carboxymethyl cellulose with alum	Desalination byproduct brine	0.2% CMC. Cost $2,250/4,047 m^2 (acre).
Petroleum emulsions	Desalination byproduct brine	4% additive. Cost $4,400/4,047 m^2 (acre).
Attapulgite clay	Desalination byproduct	2% Zeogel. Cost $1,000/4,047 m^2 (acre).
Liquid elastomeric polymer	Fresh water	Patent discloses several compositions, including polyurethane elastomers.

[a] Parks and Rosene, 1971.

equipped with centrifugal pumps, hoses, and adjustable fire nozzles have been successfully used to spray-apply polymer slurries. Any equipment suitable for dispersing a powder may be used for dusting with a polymer powder.

Dry blending forms the most effective seal and adds some structural strength to the impoundment. Other factors influencing the effectiveness of the seal are the degree of soil compaction and the composition of the impounded fluid. The limitations of the polymer seals are: the polymer itself does not supply strength, the site must be compacted; exposure to salts, acids, and multivalent cations causes the polymers to shrink, increasing the permeability and decreasing the effectiveness of the seal (Parks and Rosene, 1971).

Uniroyal (1972) conducted a study to test the feasibility of using latex as a soil sealant to prevent seepage into subterranean abandoned mines. In general, the field tests confirmed laboratory findings that latex does reduce the permeability of the soil to water, but the latex is subject to damage by microbiological attack, frost, and vegetation.

3.7 Chemical Absorptive Liners

The use of chemical absorptive liners is a new and promising concept in the lining of waste disposal facilities. This type of liner functions primarily by removing pollutants from the liquid waste as it passes through the liner mass. Chan et al. (1978) tested several clays and minerals, acidic and basic fly ash, bottom ash, activated alumina, and activated charcoal as potential chemical liners for calcium fluoride, metal finishing, and petroleum sludges. The tests were done under flow through conditions, mixing the sorbent with sand when necessary to achieve the required permeability. None of the substances alone adequately removed the hazardous or polluting compounds. However, combinations of sorbents, in a predetermined sequence, do satisfactorily remove contaminants. The type, sequence, and behavior of the sorbents varies with pH and the nature of the waste to be treated. For example, some materials remove certain metals or organics more effectively than others. The same sorbent, such as fly ash, may release ions in one pH range and absorb ions in another. Flow and nonflowing conditions also affect the absorption capacities of a material. This concept shows promise, but further testing is necessary under nonflow conditions with specific wastes to evaluate the effectiveness of various sorbents in applied situations (Chan et al.,1978).

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CHAPTER 4. LINING MATERIALS IN SERVICE ENVIRONMENTS

4.1 Introduction

In Chapter 2, the various wastes which are destined for land disposal are discussed with particular reference to their potential effects upon the integrity of liners. In Chapter 3, various materials which might be used for lining waste storage and disposal impoundments are described and their properties discussed. In this chapter, we discuss the environmental effects upon lining materials during service and the interaction of liners and wastes that might exist in service environments.

Considerable information exists regarding water resistance of materials of which linings are made, regardless of whether they are soils, asphalts, or polymeric membranes. However, the wastes, although most contain water, also contain many other ingredients which have varying effects upon lining materials. The pollutants, which liners are designed to prevent from entering the groundwater, are generally not the aggressive agents in the waste liquids; usually they are of relatively low concentrations. It is necessary to bear in mind the totality of all constituents in a waste in assessing a liner material for a given application; the chemical composition of both the waste and the lining material must be considered.

Although there is much information on the effects of water on lining materials, no similar amount of information exists on the effects on lining materials of chemicals and other fluids which might be found in the waste streams produced by varuous industries. Considerable information is available on the effects of chemicals and relatively simple mixtures of chemicals upon many polymeric materials that are used as containers, tank linings, pipe linings, and gaskets in direct contact with chemicals, solvents, and oils, but these polymers are selected and compounded for the specific application. Consequently, the EPA undertook several research programs to study the effects of waste liquids and chemicals on lining materials:

Sanitary Landfill Leachate (Haxo, 1976-1980)

Hazardous Wastes (Haxo, 1976-1980)

Flue Gas Desulfurization Sludges (Styron and Fry, 1979)

State-of-the-art Study of Liners (Stewart, 1978)

Field Verification of Liners (Pacey and Haxo, on-going)

Effect of Organic Chemicals on Soil (Brown, on-going)

In this chapter, we discuss the known effects of various wastes upon individual lining materials. Also discussed are the permeability of lining materials to wastes and gases.

4.2 Effects of Waste Fluids on Soils

Because soil permeability is the essential property which has to be considered in the case of a soil liner, any alterations of a soil due to the presence of a waste-leachate has to be identified. The most relevant characteristics which can alter soil flow properties are:

a. the dispersing/flocculating tendencies of the soil when contacted by the waste-leachate;

b. the alterations in the shrink/swell properties of the soil;

c. the change of pore-size distribution characteristics;

d. the dissolution/precipitation of chemical species, thus inducing an alteration of the proportion of soil volume available for flow, and

e. the modification of the adsorption properties of the soils.

Some of the possible changes will be indicated in the next paragraphs. Also included is a discussion of the effect of some physical properties of the waste-leachate on the performance of a soil-liner.

4.2.1 Discussion of Waste Fluids in Contact with Soils.

The composition and the relative quantities of different constituents in the soil solution are in general "equilibrium" values. The soil solution is simultaneously the cause and the effect of a particular set of properties of the soil matrix. As soon as the soil solution is changed to a foreign solution (waste-leachate) the soil itself will tend to develop new properties. This change is important since it allows us to assess the performance of the soil liner in time.

4.2.2 Waste Fluids

To determine the effect of a specific waste on the permeability of a specific clay soil liner, two unique fluids must be investigated. These are the flowable liquid constituents of the waste and the flowables generated from percolating water leaching through the waste.

A waste's flowable constituents, hereafter referred to as the primary leachate, includes both fluids in the waste (the solvent) and all components dissolved in these fluids (solutes). The primary leachate of a waste depends on the composition of the waste and may be aqueous-organic, aqueous-inorganic, organic, or sludges as discussed in Chapter 2.

Flowables generated from percolating water are composed of water (the solvent) and all the components dissolved in this water (solutes). This flowable mixture, hereafter referred to as the secondary leachate, may be aqueous-organic or aqueous-inorganic, depending on the waste's composition.

The dominant liquid or solvent phase of a waste fluid may be water or any organic fluid. The solute phase in a leachate are those chemicals that dissolve in the solvent phase. For example, in organic acids and bases, the acid or base may or may not be the solvent phase while in inorganic acids and bases, water is usually the solvent phase. Both primary and secondary waste fluids can be divided into a solvent phase and a solute phase. While the solvent phase will usually be the dominating factor controlling the leachate effect on the permeability of a clay soil liner, the solute phase also has the capacity to greatly affect clay permeability.

4.2.3 Solvent Phase of the Waste Fluids

4.2.3.1 Organic Fluid

Essentially all available literature on the behavior of organic fluids in soils relates to systems where water is the solvent (Goring and Hamaker et al., 1972). Water is viewed as the carrier fluid and the organic chemical is in trace quantities. In the case of clay liners in direct contact with concentrated organic fluids, the various equations for organic adsorption by clay minerals have limited usefulness. More relevant to organic fluids behavior in soils are basic chemical and physical properties such as dipole moment and viscosity. Table 4-1 is a list of solvent phases studied and their properties most likely to relate to their behavior in clay liners. Organic fluids placed in waste disposal facilities cover the spectrum of chemical species. The list is an attempt to select the most prevalent and representative of the fluids. The groupings of the organic fluids which will be considered are acids, bases, neutral-polar and neutral-nonpolar.

The term "organic-acid" is used to represent any organic fluid that has acid functional groups. This group of organic fluids is further divided to represent the two functional group types: phenolic and aliphatic acids. The group has the potential to be very reactive with, and mobile in, clay liners.

"Organic-base" is the group to represent any organic cation. Since these fluids are cationic, they will adsorb strongly to clay surfaces. By adsorbing to the clays, these fluids have the potential for causing volume changes in clays by changing interlayer spacings, and also of dissolving certain constituents out of the clay mineral. The two forms of organic bases represented are aromatic amines and alkyl amines.

"Neutral-nonpolar" organics are those organic fluids that have no charge and a small, if any, dipole moment. This group of fluids is further divided into aliphatic and aromatic hydrocarbons. With no charge and little dipole moment, these chemicals have the potential for moving through clay liners rapidly, and eroding the pores through which they pass, thus increasing permeability. These chemicals may also increase a clay liner's permeability by displacing water from the clay liner which may in turn cause shrinkage.

TABLE 4-1. POTENTIAL ORGANIC CHEMICALS IN WASTE FLUIDS
Relevant Physical and Chemical Properties

Organic chemicals			Temp. range of liquid state, °C		Density @ 20°C (gm/cm³)	Viscosity @ 20°C (centipose)	Dielectric constant @ 20°C	Water solubility @ 20°C (gm/l)	Vapor pressure @ 20°C (mm Hg)	Molecular weight
Type		Name	Melting point	Boiling point						
Acid	Aliphatic	Acetic acid	17	118	1.05	...	6.2	∞	11.4	60.05
Acid	Phenolic	Phenol	43	182	1.07	...		82.0	0.2	94.11
Base	Aromatic amine	Aniline	-6	184	1.02	4.4	6.9	34.0	0.3	93.13
Base	Alkyl amide	Formamide	2.6	193	...	...	110	...	...	...
Neutral-polar	Alcohol	Methanol	-98	65	0.79	...	32.6	...	92	32.02
Neutral-polar	Aldehyde	Butyraldehyde	-99	75	0.82	...	...	...	71	72.10
Neutral-polar	Alkyl halide	Chloroform	-63	61	1.49	4.7	8.0	...	160	119.38
Neutral-polar	Ketone	Acetone	-95	56	...	20.7	...	...	0.05	...
Neutral-polar	Glycol	Ethylene glycol	-13	198	1.11	19.9	...	...	...	62.07
Neutral-nonpolar	Alkane	Heptane	-91	98	0.68	0.409	...	0.003	53.0	100.21
Neutral-nonpolar	Aromatic	Benzene	5	80	0.88	0.652	2.3	1.8	76.0	78.11
Neutral-nonpolar	Alkyl benzene	Xylene	-47	139	0.87	0.810	2.6	0.20	6.5	106.16
Neutral-nonpolar	Mixed alkane	Paraffin oil	-8	~321	0.87	~28	30	...	...	~375
Water			0	100	1.0	1	78.5	∞	17.5	18.02

"Neutral-polar" organics have no charge but exhibit stronger dipole moments than the "neutral nonpolar" organics. This group of fluids is further divided to represent its functional group types: alcohols, aldehydes, glycols, alkyl halides and ketones. Their effect on permeability may be related to their effect on the clay's interlayer spacing and on changes they cause in the pore water's surface tension.

4.2.3.2 Water

Water is a unique solvent in several ways. It has a very strong dipole moment, 1.87 x 10^{-18} esu, which means a high tendency of water molecules for orientation; this property makes the water a good solvent. The proportion of dissociated water molecules on the average is very low, only one in every ten million; yet this minute ionization is essential for many reactions to occur. The dielectric constant of water (the tendency of water molecules to orient to an electric or magnetic field) is quite high (approximately 80); this is the basis for adsorption of water on clay surfaces.

At 77°F water has a viscosity of almost one centipose; this is a highly temperature-sensitive property. The significance of viscosity for flow properties was shown previously, (Section 3.2.3.4).

The surface tension of the water (71.9 dyne cm^{-1} at 25°C) is responsible for the capillary effect, water retention properties, and consequent flow properties. The tension of the soil-water interface should extend only one to two molecular layers (1.6 x 10^{-7}cm) for homogeneous surfaces. Since clay surfaces do not comply with this condition, the effect is present at much larger distances away from the surface.

Due to the sensitivity of water properties to the presence of solutes (see next paragraphs), a clayey soil liner may shrink, swell or heave, crack or pipe. Water may also increase the hydraulic gradient that moves fluids in soil. While water might not be the solvent in the waste's primary leachate, it is always the solvent in the secondary leachate.

4.2.4 Dissolved Components in Waste Fluids

Organic chemicals are dissolved in a waste's leachate, regardless of what fluid represents the waste's solvent phase. However, the relative abundance of a given organic component of the solute will depend on what the solvent is. If, for example, the solvent is a nonpolar organic fluid, it would have a large carrying capacity for solutes such as other nonpolar organics. If the solvent is water, its carrying capacity for nonpolar organics in its solute phase would be relatively small. It should be noted, however, that many organic solutes (acids, alcohols, esters, ethers, amines, ketones) reduce the surface tension of the pore water with important repercussions on shrink-swell and flow properties.

In general, inorganic compounds, particularly electrolytes, do not change the surface tension of the pore water. The presence of inorganic solutes in water is, however, important since they alter the water-clay reaction via other mechanisms with important consequences.

Probably the most relevant effect induced by the presence of electrolytes in a soil water phase is the flocculation of the clay particles. The Schultze-Hardy rule, which applies in the case of "non-specific" electrolytes, states that the flocculation value (the minimal concentration needed to flocculate a dispersed clay soil) depends on the valence of the ions of opposite charge to that of the clay particle; the larger the charge (valence), the greater the flocculating power, and the flocculating value. Van Olphen (1963) indicates an observed flocculation value of 25-150 mmol/L for trivalent ions. For negatively charged clay colloidal particles, the flocculating power of cations decreases in the order:

$$Cs>Rb>NH_4>K>Na>Li$$

For positively charged aluminum and iron sesquioxides and broken edges of a clay structure at very low pH values, the flocculating power of anions decreases in the order:

$$F>Cl>Br>NO_3>I>CNS$$

Another important feature of the clay-tactoid structure is that upon addition of a low electrolyte concentration, lower than the flocculating value, the clay becomes quite susceptible to flocculation. This can be achieved upon addition of a polar or a low dielectric constant compound.

The flocculating capacity of electrolytes operates by depressing the thickness of the "double-layer". Different types of flocculation are recognized: face-to-face (FF), edge-to-face (EF), and edge-to-edge (EE). They result in quite dfferent technological performances; thus, in dilute clay suspensions viscosity increases when EF and EE flocculation occurs and decreases when the clay flocculates FF.

Sometimes, the addition of a second compound affects the flocculation power of the electrolyte; thus, when Na-polymetaphosphate is present in the system, the flocculating value of the first compound - the electrolyte - is drastically increased, which means a tendency of the clay to be in a dispersed state. On the contrary, situations exist in which the presence of the second electrolyte lowers the flocculating value more than would have been expected if a simple additive effect of the two electrolytes would have been operative.

From the information presented in the previous section, it should be clear that apart from soil densification by compaction, soil structural features (flocculated/dispersed structures) are important for assessing the suitability of a soil liner. In this context then, a dispersed structure should be associated with a desirable condition. At present, it is believed that one of the main reactions which promotes a dispersion of the clay is the neutralization of the positively charged sites of the clay, i.e. its "broken" edges. The aluminum present in the octahedral layer forms an insoluble salt with the anion which explains the anion over-saturation of the broken-edge and, consequently, the generation of a negatively charged edge. Therefore, the presence in the water phase of any anions which have a large valency and which will tend to react with broken-edge octahedral aluminum in the manner described above, should promote at least a partial dispersion, by deflocculating the edge-to-face (EF) structure.

Another mechanism by which a clay is dispersed is cation exchange. This occurs anytime a low hydrated cation, e.g.Ca^{2+}, is replaced by a cation, e.g. Na^+, for which a thick "double-layer" is characteristic.

Highly alkaline solutions and the corresponding solutes also have a dispersion effect by the same charge-reversal mechanism. This type of peptization seems to be particularly efficient in the case of kaolinite clays (Van Olphen, 1963, p. 117).

From this succinct description, it should be clear that the presence of different inorganic compounds in the secondary leachates, their concentration, and the characteristic pH should have a profound effect on the structure of the clay and, consequently, on the performance of a soil liner.

4.3 Effects of Waste Fluids on Soils - Failure Mechanisms

4.3.1 Dissolution of Clay

Dissolution of a clay liner can be brought about by an infiltrating chemical that dissolves the exposed surfaces of a pore or channel. Either organic or inorganic acids or bases may solubilize portions of the clay structure. Acids have been reported to solubilize aluminum, iron, alkali metals and alkaline earths while bases will dissolve silica (Grim, 1953). Since clay minerals contain both silica and aluminum in large quantities, they are susceptible to partial dissolution by either acids or bases.

Pask et al. (1945) boiled several clay minerals in acid and found the percent solubilization of alumina was 3% from kaolinite, 11% from illite, and greater than 33% from montmorillonite. Grim (1968) found the solubility of clays in acid "varies with the nature of the acid, the acid concentration, the acid-to-clay ratio; the temperature and the duration of treatment." He also found that the action of an acid on clay was enhanced when the acid had an anion about the same size and geometry as a clay component. This would permit even weak acids, e.g. organic acids, to dissolve clays under some conditions.

Hurst (1970) found that the permeability of geologic formations could be increased by pumping in acetic or formic acid. Johansen et al. (1951) reported flow increases for water wells following their treatment with a solution containing citric acid. Grubbs et al. (1972) found acid waste as the probable casual agent in the permeability increase of carbonate-containing minerals. X-ray diffraction studies of the four clay minerals injected with acid waste showed them to be dissolved or completely altered. Diffraction peaks showed the most variability with montmorillonite clays.

Acidization is the name used for the process of permeability increase by acid mineral dissolution. This process is widely used to increase the permeability and hence the productivity of oil wells (Sinex, 1970).

An ever present source of organic acids in waste impoundments is anaerobic decomposition by-products. These include acetic, propionic, butyric, isobutyric and lactic acid. Anaerobic decomposition will yield the carboxylic acid derivatives of whatever organic fluids are placed in the impoundment.

Material that encrusts at the base of wells used to inject waste usually consists of calcium, magnesium and iron carbonates, along with imbedded sand and clay particles. In order to remove the carbonate compounds, they must be dissolved and then held in solution against precipitation forces. Dissolution is usually accomplished with a strong acid. At this point, calcium will reprecipitate (as calcium sulfate in the presence of sulfuric acid) unless it is chelated and removed by a flowing fluid. Chelating agents effective at preventing reprecipitation of various carbonates are citric acid, tartaric acid, and glycolic acid (Anonymous, 1977).

It is well known that strongly alkaline solutions can partially solubilize silica-containing soil constituents. Nutting (1943) showed even extremely dilute solutions of alkali to be effective at removing silica from smectites by dissolution from the crystal lattice.

4.3.2 Volume Changes in the Soil

Volume changes of soils have to be understood since their occurrence can alter the assumed density and flow properties of the soil liner.

Volume changes in clay or soil liners occur when there is a change in the water content of the clay and when the soil can overcome the overburden loading constraint. Adsorption of water on external surfaces occurs with all three clay minerals if they are below saturation. For a given change in water content, the magnitude of volume change is dependent on the clay mineral type, the arrangement of the clay particles, the size of the clay particles, the surface area per unit weight of the clay, the existing moisture conditions, and on the kind and proportion of cations adsorbed to the clay. From Table 4-2, it can be seen that montmorillonite (and, to a lesser degree, illite) may cause problems associated with changes in the volume of clay liners. Two contracted lattice sheets of montmorillonite have a 2 nm thickness. The adsorption of water on montmorillonite interlayer surfaces gives this type of clay soil the potential for greater than a 200% difference in volume between the dehydrated and hydrated state. This expandable lattice property of montmorillonite is what makes its large volume changes unique. The structure of the soil liner in operation will not be the same as the one immediately following compaction. There are at least two reasons to suspect changes of the soil structure following compaction:

a. Upon removal of compacting implements the stresses applied will relax with the result that the soil will tend to rebound to a higher void ratio. Even where this process takes place without loss of water into the atmosphere, the magnitude of negative pore water pressure will, in general, increase, and the expansion process should tend toward a larger void ratio, the value of which depends on soil elastic properties, the magnitude and persistence of stresses applied during compaction,the overburden of the point-soil element considered, the void ratio achieved at the end of compaction, etc. If superimposed on this, there is also a net loss of water in evaporation, then there will be a simultaneous reduction of the original volume of the soil. The reduction in volume can result in the

TABLE 4-2. PHYSICAL AND CHEMICAL PROPERTIES OF THE CLAY SOILS

Clay mineral	Fine clay <0.2 μm		Coarse clay 2.0-0.2 μm		Clay, %	Silt, %	Sand, %	Organic matter, %	Horizon depth, in.	pH, units	Fe_2O_3, %	Cation exchange meq/100g			Base sat. %
	%	Mineral[a]	%	Mineral[a]								Total cap.	Ca^{++}	Na^+	
Montmorillonite (Lufkin)[b]	84	MT-1	16	QZ-1 KK-2 MT-2	48.3	29.7	22.0	0.9	7-21	4.6	.42	33.6	16.1	3.3	75
Calcium saturated Montmorillonite (Houston Black)[c]	~75	MT-1 KK-3	~25	MT-1 KK-2 QZ-3	55.5	40.1	4.4	3.0	0-16	7.7	.20	60.4	...	...	...
Kaolinite (Nacogdoches)[b]	67	KH-1 MI-3	33	KK-1 QZ-2	43.2	28.0	28.8	...	7-29	5.4	...	6.2	4.5	Trace	45
Illite (Hoytville)[d]	39	I-1 MT-2	61	I-1 QZ-2	46.7	38.0	15.2	...	9-27	7.1	...	26.6	19.0	...	86

[a] MT = Montmorillonite, QZ = Quartz, KK = Kaolinite, MI = Mica or Illite, KH = Tabular Halloysite, MV = Hydrous Mica-like, I = Illite, 1 = 40%, 2 = 10-40%, 3 = <10%.

[b] Soil Conservation Service, 1976.

[c] Davidson and Page, 1956.

[d] Blevins and Wilding, 1968.

formation of microfissures which, in turn, can greatly alter the flow properties of the soil liner while in service.

b. The compaction of a soil material into a soil liner generates, at a given set of conditions, a certain characteristic structure with a corresponding void ratio and, if the internal structure of the soil is rigid, a certain set of flow properties. During compaction the equilibrium soil structure and void ratios achieved depend on the forces which oppose soil deformation, strongly correlated with the characteristic swelling pressure of the system, i.e. soil-matrix and soil-fluid compositions. Since the fluid composition during compaction is different from the composition during service exposure, changes in swelling characteristics have to be expected, and a corresponding volume change of the soil liner can result if permitted by constraining stresses.

Based on waste-effluent chemistry data, the soil engineer has to conceive a hypothetical reaction between the soil liner and the waste effluent. The testing of the hypothesis has to be performed in the laboratory using the oedometer on remolded soil specimens. The testing should generate upon compression, void ratio values similar to that encountered in the field and/or to pressure values slightly over the expected overburden in the field. The rebound curves have to be obtained in parallel with water and waste effluent. The compression and swelling indexes have to be compared and the conclusion should produce at least a semiquantitative set of information with regard to the volume changes which may be expected during the operation of the system.

An alternative, indirect, and less expensive way of predicting the swell/shrink behavior of a soil liner while in operation is to use Atterberg Limits (Sections 3.2.3.1 and 5.2.2.1) together with percentage clay content of the soil in the empirical relationship established by Seed et al. (1964).

$$S = 3.6\times10^{-5}\ A^{2.44}\ C^{3.44}$$

or

$$S = 2.16\times10^{-3}\ (PI)^{2.44}$$

where: S = percent swell under a surcharge of one psi

A = activity

C = percentage clay

PI = plasticity index.

Due to the character of these relationships, they will provide only approximate information with regard to swell. Also, to serve the present purpose, the PI in waste effluent can be determined.

If the general chemistry of the waste and the characteristics of the soil indicate that no essential volume change of the soil liner will occur, then the soils engineer should review the most preeminent elements which determine the shrink/swell characteristics of a soil system. Acccording to Mielenz and King (1955) these elements are: the kind and amount of clay minerals present in the soil, exchangeable composition, electrolyte concentration of the soil solution, particle size distribution, void size characteristics, soil structure, and opposing normal load.

In this discussion on volume-change characteristics of a soil, it was tacitly assumed that the greater the tendency of a soil to change its volume, the more drastic the changes in flow-properties can be expected. While this seems to be a logical conclusion, the quantification of such a statement is lacking at the present time, but it is certainly true for our case in which the original soil solution is changed in the long run for the waste effluent. In the general swelling of a soil, an increase in void ratio should increase soil permeability since a larger proportion of the total soils volume is available for flow. In our particular situation, this may very well not be the case, because simultaneously with the volume increase, a change in pore size distribution will occur and with it a decrease in the median pore size of the soil. This latter effect can easily offset the volume increase tendency of the soil and thus result in a lower permeability of the soil.

Ideally, a soil specimen should be treated with the waste-effluent in a realistic way, its mechanical behavior observed, and any alterations in flow properties recorded. The final argument for using a particular soil as a liner (apart from its attenuating capacity) is its resistance to the flow of waste effluent into underlying, undisturbed soil.

4.3.2.1 Shrinkage and Cracking

Extraction of interlayer water causes the shrinking and associated cracking exhibited by montmorillonitic soils (Baver et al., 1972; Grim, 1968). Cracking is a result of the clay undergoing three dimensional shrinkage. Where the rate of water extraction is not uniform, cracks will form in wetter soil (Yong and Warkentin, 1975). The water content of a clay liner may change if an organic leachate displaces the water from the clay liner. To understand more fully how much water will be displaced by what organic fluids, it is necessary to first understand the nature and forms water takes in a clay liner.

In clay liners, the clay particles are initially surrounded by multiple layers of water. The thickness of the water between adjacent montmorillonite lattice sheets will effect the plasticity, interparticle bonding, compactibility, and water movement within a clay liner. These properties change as the thickness of the interlayer water changes (Yong and Warkentin, 1975).

Examination of the forces holding water to the interlayer surfaces in montmorillonite will assist in predicting the effects of an intruding organic leachate on the interlayer spacing.

It is widely believed that water layers immediately adjacent to montmorillonite interlayer surfaces are nonliquid, hexagonally structured, and held much more strongly than water layers further out from the surface (Grim, 1968).

The thickness of this structured water varies depending on the adsorbed cation. Montmorillonite has a structured water thickness of 1 nm or four water layers per clay surface where calcium is the adsorbed cation. Sodium montmorillonite gives a structured water thickness of 0.75 nm or 3 water layers on its surfaces (Grim et al. 1945). Glaeser (1949) found the distance between dehydrated montmorillonite layers exposed to acetone was 1.25 nm and 1.51 nm where sodium and calcium, respectively, were the adsorbed cations.

These surface-bound layers of water are held strongly to the clay. They represent however only a part of the interlayer water. The water layers further out from the clay surfaces are held in place by the large polarity of water reinforced with its ability to hydrogen bond. This water chain extends back to the structured water layers anchored to the clay surface. The outer layers of water would easily be displaced by an intruding fluid. Where the replacing fluid has a low dipole moment, a decrease in interlayer spacing would probably result. If the intruding fluid had a higher affinity for the clay surface than the structured surface layers of water, an even greater decrease in interlayer spacing should be possible.

It may be possible for fluids with a high dielectric constant to displace interlayer water. High dielectric constants in a fluid tend to ionize the molecular species in the fluid. Ionization in turn increases the amount of adsorption onto clays for the ions. Asphaltenes and resins from the heavy end of a crude oil were found to adsorb more readily to montmorillonite when they were suspended in solvents of high dielectric constant (Clementz, 1976). A major conclusion of the Clementz study was that ionized asphaltenes in an aromatic solvent with a high dielectric constant may displace water from the clay surface irreversibly. Consequently the clay was hydrophobic and had its cation exchange capacity (CEC) reduced 52%. This CEC decrease would increase the permeability of a clay to charged or polar organic chemicals.

When a fluid adsorbs to a surface, that surface is said to be wetted by the fluid. Clay surfaces in a clay liner are water-wet initially. If a permeating organic fluid has a higher affinity for the clay surface, the clay may become organic-wet. Petroleum engineers commonly refer to surfaces with oil adsorbed as being oil-wet (Raza et al., 1968). Water and oil are said to compete with each other for solid surfaces in oil reservoirs. A quantitative measure of the preferential wettability of a clay surface for water and an organic fluid can be represented as the difference between the water-clay and organic-clay interfacial energies as represented by the Yong-Dupre equation (Adams, 1941).

$$(E_{org:c}) - (E_{w:c}) = (E_{org:w})\ (\mathrm{Cos}\ \theta)$$

where:

$E_{org:c}$ = interfacial energy per unit area between the organic and clay (dyn cm^{-1})

$E_{w:c}$ = interfacial energy per unit area between the water and clay (dyn cm^{-1})

$E_{org:w}$ =interfacial energy between the organic and water (dyn cm $^{-1}$)

θ = angle at the organic:clay:water interface measured through water, (degrees).

There is no direct method for measuring either the organic:clay or the water: clay interfacial energy (Raza et al., 1968). Their difference, however, is equivalent to the product of the water:organic interfacial energy and the cosine of the water:clay:organic contact angle. This contact angle is easily calculated from capillary rise measurements of the fluids.

If an intruding organic leachate displaces the anchored water layers, there will be no forces holding the balance of the interlayer water against gravitational drainage forces. In this case montmorillonite interlayer spacing would decrease from 2 nm to whatever the interlayer spacing value would be for the newly adsorbed organic fluid. Table 4-3 is a list of the interlayer spacings for clay minerals after exposure to organic fluids. There is an abundance of x-ray diffraction data for clay minerals with correlations to the interlayer cation, dehydration temperature and the immersion fluids pH, dielectric constant, and concentration (Grim, 1968; Theng, 1974; Barshad, 1952). The usefulness of this data is limited because as a matter of standard procedure, the clay minerals are initially dehydrated. In order to simulate more closely the situation in a clay liner, there needs to be a series of x-ray diffraction studies on hydrated clay minerals. First, x-ray diffraction data is needed for the clay liner saturated with water as it would be prior to the impoundment of a waste. Secondly, x-ray diffraction data is needed for the same clay liner after organic leachates have permeated the clay. If a substantial interlayer spacing decrease is observed for the second set of x-ray diffraction data, shrinkage cracks may be anticipated for that particular liner-waste combination.

It is interesting to compare the interlayer spacings for an organic fluid at different dehydration temperatures (Table 4-3). Dehydration at higher temperatures removes more of the strongly adsorbed interlayer water. Subsequent treatment with the organic fluid yields lower interlayer spacings for the clay dehydrated at the highest temeprature. This is true to a lesser degree when sodium rather than calcium is the interlayer cation. When the clay is dehydrated at room temperture (20°C) there is still water coating its surfaces. However, both a neutral polar compound (N-butanol) and a neutral nonpolar mixture (paraffin oil) reduced the interlayer spacing of the clay dehydrated at 20°C over the interlayer spacing of the clay treated with water only after dehydration. This indicates that even compounds less attracted to a clay surface than water can displace some of the interlayer water and decrease interlayer spacing. If this scenario were to take place in a clay liner, even such common neutral nonpolar organic solvents as xylene, benzene, heptane or paraffin oil may decrease interlayer spacings and cause shrinkage cracks in clay liners.

Another factor that will influence the interlayer spacing in montmorillonite is the orientation of an organic interlayer cation. Greene-Kelly (1955) found the interlayer spacing of the clay with aniline adsorbed depended on the

TABLE 4-3 INTERLAYER SPACINGS OF CLAY ORGANIC COMPLEXES ON MONTMORILLONITE[a]

Compound	Interlayer spacing Ca sat.	Interlayer spacing Na sat.	Dielectric constant 20°C	Dipole moment	Dehydration temp., °F
Benzene	.99	.99	2.3	0	250
Benzene	1.52	.99	2.3	0	150
Methanol	1.71	...	32.35	1.66	250
Ethanol	1.70	1.34	25.00	1.70	170
Ethanol	1.70	1.35	25.00	1.70	250
n-Butanol	1.52	1.32	17.70	1.66	20
n-Butanol	1.45	1.32	17.70	1.66	170
n-Butanol	1.45	1.32	17.70	1.66	250
n-Decanol	3.68	...	5.0	1.7	250
Paraffin oil	1.45	...	2.10	0	20
Paraffin oil	9.9	...	2.10	0	250
Water	1.92	...	78.5	...	250
Methyl ethyl ketone	1.73	...	18.85	2.74	250
β-Alanine	2.5	...	150.0	...	250

[a] Barshad (1952).

concentration of aniline. Table 4-4 gives the interlayer orientation and spacing with several aniline concentrations on a montmorillonite clay.

In a waste impoundment, the affinity an organic leachate has for the hydrated clay surfaces will determine if it will displace the in-place water. Since the clay surface is negatively charged, organic leachate components that are polar or positively charged will have an affinity for clay surfaces. Since the water on the clay surface is several layers thick, water solubility will also improve an encroaching fluid's access to the clay surface. The strength with which water is held to a clay surface will vary with the cations adsorbed to the clay and the charge density of the clay. These factors may change from one place to another in a clay liner. In order to predict interlayer spacing and permeability of inplace clay liners, a series of x-ray diffraction studies

TABLE 4-4 INTERLAYER ORIENTATION AND INTERLAYER SPACING IN MONTMORILLONITIC CLAY [a]

Sorbed fluid	Orientation	Interlayer cation (meq/g)	Interlayer spacing (nm)
Aniline	Upright	Na (SAT)	1.50
H_2O	Flat	Aniline (0.62)	1.28
H_2O	Upright	Aniline (0.91)	1.42
H_2O	Upright	Aniline (SAT)	1.50
H_2O	Upright	Aniline (SAT)	1.52

[a] From Greene-Kelly, 1955.

should be undertaken on the range of liner-waste combinations likely at a given waste disposal site. If the leachate contains organic cations, the charge density of the clay will affect the resulting interlayer spacing. Weiss (1963) found the interlayer spacing after exposure to alkylammonium ions to be 1.3 nm, 1.9 nm and 2.76 nm for montmorillonites with low, medium, and high charge density respectively.

A recent review of the interactions between montmorillonite and its interlayer water is given by Low (1979).

4.3.2.2 Swelling

Swelling behavior in clays is dependent on what clay minerals are present. Both kaolinite and illite are relatively low swelling while montmorillonite is high swelling (See Table 4-2). Kaolinite and illite show the greatest volume decrease on initial dehydration and very little swelling on subsequent rewetting (Yong and Warkentin, 1975). This characteristic would limit the capability for these two clays to "self heal" or to close shrinkage cracks once they form. Montmorillonite clays exhibit both large and reversible volume changes under normal conditions. However Gieseking (1939) found that montmorillonite lost its ability to "self heal" or swell when exposed to organic cations.

Hughes (1975) found three main mechanisms responsible for the reduction or reversal of swelling in sodium bentonite (a clay in the montmorillonite family):

a. Adsorption of organics by the clay surfaces interferes with clay-water interactions and blocks further swelling.

b. The exchange of monovalent sodium for divalent calcium on the clay surface causes a reduction and reversal in swelling.

c. Excess sodium will compete for available water with clay surfaces, causing a decrease in the thickness of the water shell surrounding the clay.

Clay structure refers to the arrangement of the plate-like clay particles. The two extremes in this structure are the flocculated or edge-to-face arrangement and the dispersed or face-to-face arrangement. Different sets of forces are acting to attract and repulse clays from each other in these structural forms. The forces acting on the clays also change with ion concentration, ion valence, dielectric constant of the fluid around the clay, temperature, size of the ions in both the hydrated and dehydrated states, pH, and the clay's anion exchange capacity (Lambe, 1958).

It should be understood that organic leachates may cause either shrinking or swelling of clay liners. Barrier (1978) reported swelling of montmorillonite clays as a result of exposure to several forms of acetonitrile, xylene, cyclopentane, alcohols, glycols, and ketones. A liner that swells and heaves may loose its integrity during heaving, or it may shrink later when water replaces imbibed organic fluids.

A clay's potential for volume change can be significantly related to its Atterberg limit values. Table 4-5 shows these relationships for clays of three swell potentials (Holtz and Gibbs, 1956). However, an actual quantification of a clay's swell potential would be much more complex. Some of the factors listed by Bowles (1979) as effecting swell behavior in soils were clay type, surcharge load, void ratio, method of saturation, and general environmental conditions.

Table 4-5. SWELL POTENTIAL VERSUS ATTERBERG LIMIT VALUES IN THREE CLAY SOILS

	Swell potential		
	Low	Medium	High
Plastic range[a]	0-30	30-50	>50
Shrinkage limit[b]	> 12	10-12	<10

[a] The range of water contents below which the clay will behave as a fluid and above which it loses its cohesiveness.

[b] The water content of a clay below which no further shrinkage occurs.

It has been suggested that potential swelling is mineralogically determined, and that exchangeable cations "perturb" rather than dominate the swell-shrink characteristics (Ravina and Low, 1972).

Soil volume-change represents a very important potential mechanism of failure of a soil liner.

4.3.3 Piping

Underseepage as the result of soil piping is an ever present danger in earthen dams. Mansur and Kauffman (1956) describe piping as "the active erosion... pressure and the concentration of seepage in localized channels." Jones (1978) found the early stages of piping development to be associated with vertical contrasts of the structure and permeability in soils. Soil piping was also associated with shifts in a soil pore size distribution toward macropores with no corresponding change in total porosity. A reactive fluid may enlarge the surface area of a pore by dissolution of the pore wall and by the dissolution of the soil matrix between two pores. While a fluid's reactivity is reduced by its action on the pore wall, the size increase of the pore will increase the turbulent character of the flow inside the pore and consequently the erosion power of the moving fluid. In this manner, any variability in the pore size distribution of a clay liner may be magnified with time. Schechter and Gridley (1969) found that wormhole formation was the result of a reactive fluid's preferential flow in larger pores. He went on to say that a quasi-equlibrium is reached where further growth in a pore is limited by the rate of diffusion of the reactive fluid.

Seepage by reservoir water into dams has been reported to have caused dispersive piping and eventual tunneling all the way through earth dams. Tunneling was reported to occur in soils with a local permeability of 1×10^{-5} cm s^{-1}.

Differential solution and subsequent leaching, especially with calcareous sediments, was reported to result in the formation of channels, sink holes and cavities (Mitchell, 1976). In this respect dissolution (the first mentioned failure mechanism) seems to be in some circumstances a precondition for piping.

Cedergren (1967) reported that differential leaching of limestone, gypsum and other water soluble mineral components can lead to development of solution channels that get larger with time and substantially increase permeability. He warned not to underestimate the importance of minor soil and geologic details on the permeability of soil formations as they cause the majority of failures in dams, reservoirs and other hydraulic structures.

Cedergren (1967) concluded that most failures caused by seepage can be placed in two categories:

a. those that are caused by soil particles migrating to an escape exit, causing piping and erosional failures; and

b. those caused by uncontrolled seepage patterns which lead to saturation, internal flooding, and excessive seepage.

Crouch (1978) found that so called tunnels, tunnel-gullies, or pseudokarsts will develop in dispersive soils where the soil-colloid bond strengths are low compared to the energy of water flowing through the soil. He found dispersive soils or those with low structural stability have been associated with tunnel erosion throughout the world. Other factors found to be related to tunnel erosion were ESP (exchangeable sodium percentage), soil cracks, low permeability, and hydraulic gradients.

In a study of the variables effecting piping, Landau and Altsehaeffl (1977) noted a strong interaction between the chemical composition of the eroding water and compaction water content. Ion concentration seemed to have little effect on soil piping susceptibility for mixed illitic and kaolinitic clay loam compacted dry of optimum. For the same soil compacted wet of optimum, soil piping susceptibility was highly related to ion concentration in the eroding water. When low ion concentration eroding water is combined with wet-of-optimum compaction, Landau and Altschaeffl (1977) reported low resistance to internal erosion.

Piping involves the slaking of soil particles. Slaking is defined as the disintegration of unconfined soil samples when submerged in a fluid. Moriwaki and Mitchell (1977) investigated the dispersive slaking of sodium and calcium saturated kaolinite, illite, and montmorillonite. All the clays slaked by dispersion when saturated with sodium with the process proceeding faster with sodium kaolinite and sodium illite. Sodium illite swelled slightly while dispersion of sodium montmorillonite was preceded by extensive swelling. Sodium kaolinite underwent no visible swelling while dispersing. For the calcium saturated clays, illite dispersed much more slowly while the rate of dispersion increased for kaolinite and montmorillonite. Calcium kaolinite was thought to disperse faster because of its higher permeability relative to sodium kaolinite. Sodium montmorillonite was thought to disperse slowly because the large degree of swelling it underwent would lower permeability, thus slowing water entry and retarding dispersion.

Compaction has been shown to decrease the electrolyte content of expelled interlayer water (Rosenbaum, 1976). Such a lowering of fluid electrolyte concentrations in sodium-saturated clays may cause substantial swelling and dispersion (Hardcastle and Mitchell, 1974). This dispersion causes particle migrations. If there are fluid conducting pores large enough to transport these dispersed clay particles, permeability increases and soil piping may result (Aitchison and Wood, 1965).

It is important to note that piping would initiate on the underside of a clay liner where clay particles could migrate into a substrata with larger pore diameters. The soil pipe would then progress upward through the clay liner until it finds an opening into the waste impoundment. Clay particles have been shown to migrate through porous media containing less than 15% clay (Hardcastle and Mitchell, 1974). Consequently, clay liners underlain by soils containing less than 15% clay may be susceptible to soil piping.

Four laboratory tests for the determination of soil susceptibility to dispersive erosion have been developed by the U.S. Soil Conservation Service. A major conclusion of a recent symposium on soil piping was that these four tests should be performed on soils where piping would cause unacceptable damage (Sherard and Decker, 1977). The four tests are the pinhole test, a test of dissolved salts in the pore water, the SCS dipsersion test, and the crumb test. For the test methods and extensive test data see ASTM Special Technical Publication #623.

4.3.4 Alteration of the Permeability of "as-compacted" Soil

Possible changes in the "as-designed" permeability can occur due to unpredicted volume changes taking place in the soil liner during the operation caused by piping or directly by a change in soil structure without any change of soil bulk volume.

As discussed in Section 3.2.3.2, the soil liner should be compacted at a high moisture content, relatively high density and, a dispersed clay-structure; this situation will lead to the lowest possible permeability in "as-compacted" state. In this condition, soil matric potential will have a relatively high value (in the low negative range) and the incoming fluid (waste leachate) will arrive as an unsaturated flow; therefore, the rate of wetting of the soil element will be quite low. Under these circumstances, the initial swell of the soil would be quite limited.

If, on the other hand, the waste fluid is very different in its chemical composition from the water used during compaction, the incoming solution will replace the original clay interlayer water and establish a new flocculation/dispersion equilibrium. This may lead to volume changes, the significance of which cannot be inferred from general knowledge. A rigorous testing program can partially reveal soil volume change vulnerability and complementary consequences on flow properties.

The occurrence of piping in dams is to a considerable extent connected with the sharp boundary between two very different soil materials making up the structure. If, in the case of a soil liner the underlying soil is texturally very different, a high probability of piping can exist. If, associated with this, the chemical composition of the waste fluid is such that internal erosion of the soil liner is possible, the integrity of the liner becomes questionable. However, the most relevant change resulting in the overall increase in soil liner permeability is probably the modification of soil structure.

In different parts of this Manual, particularly in Section 4.2, emphasis is placed on the importance of the soil structure as reflected by the pore size distribution. Also, the testing program discussed in Section 5.2 should reveal the chemical sensitivity of the soil, i.e. its tendency to modify its internal structure without mechanical deformation.

4.3.5 Slope Stability

When the topography of the waste-disposal site is flat, soil strength characteristics are of little consequence. However, environmental and economic criteria often prevail in the process of choosing a waste disposal site; environmentally, such a site should be placed as far away as possible from highly populated areas, and since these are mostly flat areas; the disposal sites will be pushed into hilly dissected topographical regions; economically, a hilly region has its advantages in the sense that placing a waste in a ravine, for instance, may involve generally less earth work and result in a higher efficiency of waste-storage per unit disposal area. Consequently, in many situations, the waste-disposal site floor will be sloping and so will the soil liner. A similar situation occurs even when the floor of the waste-disposal site is flat, but the waste is buried under the ground surface. In this case the waste-disposal "site" will have a trapezoidal cross section with lateral slopes. The consolidation of the waste during the storage time can result in uncovering of slopes, relief of lateral pressures, and possibly an unstable condition. For these situations, an investigation of stress-strain and strength properties of the soil has to be conducted. The difficulties associated with the analysis of slope stability are not associated with the usual difficulty in determining properly the cohesional and frictional characteristics of the soil, but rather with a proper estimation of the characteristic hydrology of the site under operation condition; in other words, changes in the hydrology have to be estimated, average and "worst" patterns have to be identified, and all information integrated into a factor of safety using pertinent methods of analysis.

Although slope stability considerations are important, we believe that due to the vast amount of available information on this subject, the design of the slope can be done in such a way that a factor of safety larger than 1.4 - 1.5 can be generated. The problem is slightly more complicated when there is a partial replacement of soil water by waste-leachate; the design of the slope cannot be done without considering this factor.

In Section 5.2.2.5, the influence of different factors upon soil strength are presented and suggestions are made regarding the testing of the soils for strength.

The failure of a sloped soil liner can occur as a slippage of the whole compacted layer over the undisturbed soil or bedrock. Another mechanism is the creep of very cohesive saturated clays; by this mechanism tension can be generated in a slope and cracks perpendicular to the slope can enhance failure.

We define all these conditions as "failure", since they will lead to changes in the integrity of the soil liner with adverse effects upon bulk soil flow-properties.

4.3.6 Miscellaneous

There are a variety of situations that may increase the permeability of clay liners other than those discussed above. The phenomena causing the permeability increase may not be fully understood, but they are presented here for their possible usefulness in future research.

Miller et al. (1975) found that the permeability of a soil increased as water flushed out an earlier application of surfactant.

Grubbs et al. (1973) found that methyl alcohol increased the permeability of a core previously injected with oil-base wastes. He also noted the use of solvents, organic acids, surfactants, alcohols, and emulsion breakers for permeability enhancement in deep well injection operations.

Letey et al. (1962) observed for water-repellent soils an increase in the infiltration rate with time. He felt this was due to the progressive neutralization of the soils' water repellency as the depth of infiltration increased. In a later study, Miller et al. (1975) found that permeability increases with time if there is a substance in the soil that would dissolve into the water and decrease its surface tension.

Brant (1968) found an increase in the water permeability after a soil was treated with para-tert-butylcatechol. He postulated that the increase was due to the soil matrix being rendered more stable to water flow yielding a decrease in the migration of soil particles.

Watson (1968) found surfactants acted to stabilize soils against dispersion and swelling, thereby preventing a decrease in permeability values at certain surfactant concentrations.

Wolstenholme (1977) stated that solvents of low viscosity are "by their very nature" leachable and able to extract organic components from otherwise dry waste. Low viscosity would significantly increase a fluid's permeability according to Darcy's Law.

4.4 Effects of Waste Fluids on Flexible Polymeric Membrane Liners

4.4.1 Introduction

Background information obtained in the field on the effects of waste fluids on flexible membrane liners is limited. Consequently, most of this discussion of liner materials to various waste fluids will be based upon laboratory and simulated exposures. The principal experience in the field with membrane liner materials has been with water impoundment and conveyance. There also has been some experience with the impoundment of brines. The experience with waste fluids, however, is relatively recent although membrane lined impoundments for waste water have been used since the 1960's.

Use of polymeric membrane liners for water conservation was started in the 1940's and the first membranes were used for lining canals in 1948. These liners were butyl-coated fiberglass. Later, a number of water reservoirs, catchment basins, canals, and ponds were lined with butyl sheeting (A.R. Dedrick, 1980; W. S. Smith, 1980; Lauritzen, 1967). A variety of other polymeric membrane liners were also developed based upon such polymers as: polyvinyl chloride (PVC), polyethylene (PE), chlorosulfonated polyethylene (CSPE or CSM), and chlorinated polyethylene (CPE). These were all used in the conservation, collection, storage, and conveyance of water.

Use of polymeric membrane liners for lining waste disposal sites began in the early 1970's principally because their low permeability appeared to be effective for preventing the migration of toxic constituents from waste sites. At that time, little was known as to the effects wastes would have on polymeric membranes and how long the service lives of liners might be.

Because of the potential impact that pollutants from waste disposal sites might have on the groundwater, the EPA initiated research work in this area. They desired to determine the state-of-the-art with respect to liners and to assess the various liners available under conditions which simulated as closely as possible actual service conditions. EPA felt that the test results from this type of evaluation would give the greatest credibility to the using community and to the public-at-large.

Two EPA projects have been undertaken to assess the effects of various wastes upon a wide spectrum of potential liner materials which have been used in the handling of water. The first project dealt with the exposure of lining materials to sanitary landfill leachate and the second with similar types of liners to hazardous wastes. These liner materials included flexible membranes, soils, and various admixed materials. The membrane materials selected for these studies were commercially available in 1973-1975 and were tested, if available, at a single thickness of 30-40 mils. In this section, the available results of the exposures are summarized and the methodology briefly described. These projects are reaching completion and final reports will be forthcoming in the early part of 1981.

4.4.2 Exposure of Membrane Liners to Sanitary Landfill Leachate

To evaluate membrane liners exposed to landfill leachate, liner specimens, two feet in diameter, were placed under eight feet of ground refuse in landfill simulators (Figure 4-1). An individual simulator consisted of a two-foot diameter steel pipe, ten feet in height, placed on an epoxy-coated concrete base (Figure 4-2). The specimen was sealed into the base with epoxy so that leachate could not bypass the liner. Each liner specimen had a seam through the center which was either made by the manufacturer or in the laboratory in accordance with the standard practice recommended by the supplier. Approximately one cubic yard of ground refuse was compacted above each liner in approximately four-inch lifts to yield a density of 1240 pounds per cubic yard at a 30 percent water content. The refuse was covered with two feet of soil and four inches of crushed rock.

Tap water was introduced at the rate of 25 inches per year. Leachate generated in each cell was ponded above the specimen at a one-foot head by continually draining into a collection bag. Any leachate which seeped through the liner was collected below the liner.

In addition to the primary liner specimens, 2.5 x 22 inch specimens were buried in the sand above the liner and were thus totally immersed in the leachate. Two sets of each material were exposed in the simulators. One set of simulators was dismantled at the end of one year and the second set at the end of five years. Additional immersion testing was performed outside the simulators by passing leachate through cells in which 8 x 10 inch specimens of the membrane liners were hung. The specimens that were removed from the simulators and from the immersion cells were subjected to a range of physical

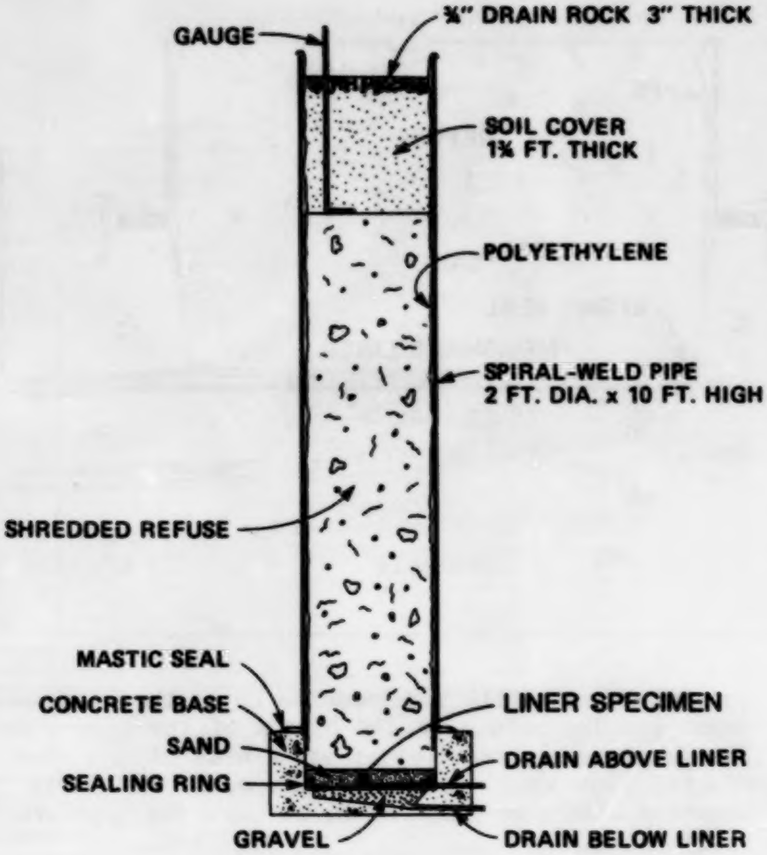
GAUGE
¾" DRAIN ROCK 3" THICK
SOIL COVER
1¾ FT. THICK
POLYETHYLENE
SPIRAL-WELD PIPE
2 FT. DIA. x 10 FT. HIGH
SHREDDED REFUSE
MASTIC SEAL
CONCRETE BASE
SAND
SEALING RING
GRAVEL
LINER SPECIMEN
DRAIN ABOVE LINER
DRAIN BELOW LINER

Figure 4-1. Landfill simulator used to evaluate liner materials exposed to sanitary landfill leachate.

tests normally performed on rubber and plastic materials. These tests are listed in Table 4-6.

TABLE 4-6. TESTING OF POLYMERIC MEMBRANE LINERS
Before and After Exposure to Wastes

Thickness
Tensile strength and elongation at break, ASTM D412
Hardness, ASTM D2240
Tear strength, ASTM D624, Die C
Water absorption or extraction at RT and 70°C, ASTM D570
Seam strength, in peel and in shear, ASTM D413
Puncture resistance, Federal Test Method Standard No. 101B, Method 2065
Water vapor transmission, ASTM E96
Density and ash
Volatiles and extractables

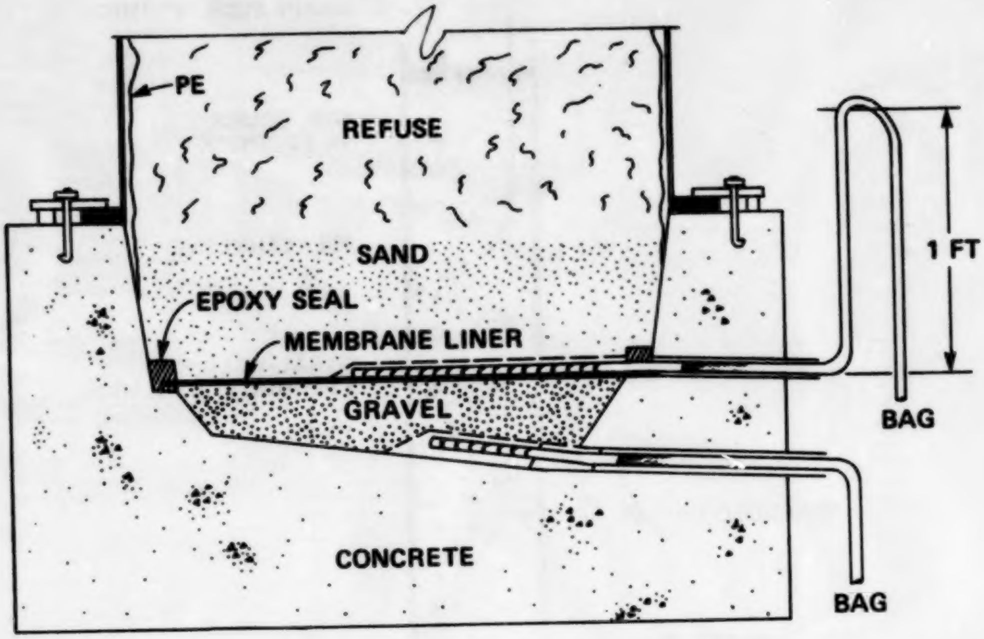

Figure 4-2. Base of the landfill simulator in which the liner materials were exposed. The refuse at the bottom of the column was anaerobic. The leachate was maintained at a head of one foot by U-tubes. Plastic bags were sealed at both outlets. Strip specimens of membrane liners were buried in the sand for exposure to leachate.

A comparison of the swelling of membrane materials in water and in leachate is presented in Table 4-7. The composition of the leachate at the end of the first year of operation of the simulator is presented in Table 4-8. The data show that the swelling in leachate is significantly higher than that in water in spite of the dissolved inorganic constituents in the leachate. This increase in swelling is probably due to the organic constituents in the leachate.

In Table 4-9 the absorption of the primary and buried liner specimens after twelve months of exposure to leachate is compared with samples of similar materials immersed in leachate for 8 and 19 months. The data show that the buried specimens which are exposed on both sides to the leachate tend to swell slightly more than the primary specimens which are exposed to the leachate on only one side. The swell of the specimens, that were immersed completely in leachate which flowed by the specimens as they were hung in the immersion cells, was equal to or greater than the swell of the buried specimens. Leachate flowed by the latter specimens but at a slower rate.

Overall, these results indicate that the leachate tends to swell the membranes more than does water and that exposure from two sides yields somewhat higher swelling values. In some cases, there was a levelling off with time of the

TABLE 4-7. WATER AND LEACHATE ABSORPTION BY POLYMERIC LINERS[a]
(Data in percent absorbed by weight)

	Liner no.	Water-RT 1 year	Leachate 1 year
Butyl rubber	7[b]	1.60	1.78
	22	1.70	2.32
	24	1.10	1.0
Chlorinated polyethylene (CPE)	12[b]	13.10	9.0
	13[c]	19.60	12.4
	23	15.50	10.3
Chlorosulfonated polyethylene	3	17.40	20.0
	4[c]	18.00	19.0
	6[b, c]	9.20	13.64
	14[c]	11.20	8.71
Ethylene propylene rubber (EPDM)	8	1.40	5.95
	16[b]	4.80	5.50
	18	...	...
	25	1.50	5.99
	26	1.60	8.99
Neoprene	9	22.7	8.73
Polybutylene	20	0.25	0.33
Polyethylene	21[b]	0.20	0.25
Polypropylene	27	0.28	0.40
Polyvinyl chloride	10	1.85	6.72
	11	1.85	5.0
	15	2.10	4.64
	17[b]	1.85	3.29
	19	0.60	0.75

[a] Haxo, 1977.

[b] Liners mounted in generator bases.

[c] Fabric-supported liner.

degree of swelling by the leachate. However, the composition of the leachate was simultaneously changing, with the level of the organic constituents dropping.

TABLE 4-8. ANALYSIS OF LEACHATE[a]

Test	Value
Total solids, %	3.31
Volatile solids, %	1.95
Nonvolatile solids, %	1.36
Chemical oxygen demand (COD), g/l	45.9
pH	5.05
Total volatile acids (TVA), g/l	24.33
Organic acids, g/l	
Acetic	11.25
Propionic	2.87
Isobutyric	0.81
Butyric	6.93

[a] At the end of the first year of operation when the first set of liner specimens were recovered

Source: Haxo, 1979.

TABLE 4-9. SWELLING OF MEMBRANE LINERS BY LEACHATE[a]
(In percent weight increase)

Membrane Liner	In landfill for 12 months Primary specimens	Buried specimens	Immersed in leachate 8 mo.	19 mo.
Butyl rubber	2.0	1.8	1.4	2.6
Chlorinated polyethylene	6.8	9.0	7.9	14.4
Chlorosulfonated polyethylene	...	20.0	18.6	22.8
	12.8	13.6	12.1	14.9
Ethylene propylene rubber	5.5	6.0	2.9	3.8
Polybutylene	...	0.3	-0.2	0.7
Polyethylene	0.02	0.3	0	0.2
Polyvinyl chloride	...	5.0	2.4	4.4
	3.6	3.3	2.3	4.4
	...	0.8	0.9	1.9

[a] Haxo, 1979.

Typical of the results which have been obtained on the exposure to leachate are those shown in Figures 4-3 through 4-5 regarding absorption of leachate, tensile strength retention, and relationship of retention of tensile strength and leachate absorption for various membrane lining materials that were immersed in leachate for 8 and 19 months. The effects of 8 month and 19 months of immersion in leachate upon the S-200 modulus of the membranes are shown in Table 4-10.

In Figure 4-3 the specific membranes are numbered on the bars. The length of the bars show the range of absorption values obtained for a liner material of a given polymer type. For example, one neoprene liner at 8 months swelled approximately 2% and another approximately 20%; at 19 months the spread had become 3% and 32%, respectively. Similar effects were observed for the values of modulus and of tensile strength (Figure 4-4).

In Figure 4-5 the retention of tensile is plotted against the leachate absorption for all pairs of data points measured at 8 and 19 months. These data show a general downward trend of tensile strength with increasing leachate absorption. Much of the loss in tensile strength can be attributed to swelling *per se* and the reduced amount of rubber in the cross-section of the tensile test specimen.

4.4.3 Exposure of Membrane Liners to Hazardous Wastes

The second contract was concerned with the laboratory evaluation of a wide range of liner materials, including membranes, on exposure to a variety of hazardous wastes. Our basic approach was to expose specimens of the various commercial lining materials under conditions which simulated real service, using actual wastes, to measure seepage through the specimens, and to measure effects of exposure by following changes in important physical properties of the respective lining materials.

In this study, various membrane lining materials were subjected to seven types of exposure testing:

- Bench screening tests; small specimens immersed in wastes.
- Primary exposure cells; one-side exposure to waste.
- Weather test; roof exposure.
- Weather test; small tubs lined with membranes and containing wastes.
- Water absorption at room temperature and 70°C.
- Membrane bags containing wastes in deionized water; one-side exposure.

The above exposure conditions are discussed and tests presented:

1. Primary exposure tests.
2. Immersion tests of membranes.
3. Pouch test of membranes.

TABLE 4-10. RETENTION OF MODULUS[a] OF POLYMERIC MEMBRANE LINER MATERIALS ON IMMERSION IN LANDFILL LEACHATE

Polymer	Liner no.	S-200, psi Unexposed	S-200, psi 8 mo.	S-200, psi 19 mo.	Retention % of original value 8 mo.	Retention % of original value 19 mo.
Butyl rubber	44	685	590	620	86	90
Chlorinated polyethylene	12	1330	1130	1190	85	89
	38	1205	1070	1090	89	90
	86	810	790	860	98	106
Chlorosulfonated polyethylene	3	735	395	335	54	46
	6[b]	1550	1775	2070	114	134
	85	1770	1360	1920	77	108
Elasticized polyolefin	36	970	1005	1050	104	109
Ethylene propylene rubber	8	690	870	860	126	124
	18	760	840	830	110	109
	83[b]	845	905	900	107	107
	91	855	775	790	91	92
	41	1040	1035	1030	100	99
Neoprene	9	1235	975	950	79	77
	37	1635	1630	1640	100	100
	42[b]	-	-	-	-	-
	90	1190	1245	1350	105	114
Polybutylene	98	3120	3160	3150	101	101
Polyester elastomer	75	2735	2790	2670	102	98
Polyethylene	21	1260	1340	1285	106	102
Polyvinyl chloride	11	2120	1845	1805	87	85
	17	1965	1570	1640	80	84
	19	1740	1545	1645	89	94
	40	1720	1560	1570	91	91
	67	1700	1570	1780	92	105
	88	2400	1900	2105	79	88
	89	2455	2370	2330	96	95
Polyvinyl chloride + pitch[c]	52	1020	870	880	85	86

[a] Average of stress at 200% elongation (S-200) measured in machine and transverse directions.

[b] Fabric reinforced.

[c] S-100 values given; original and subsequent exposed specimens failed at less than 200% elongation.

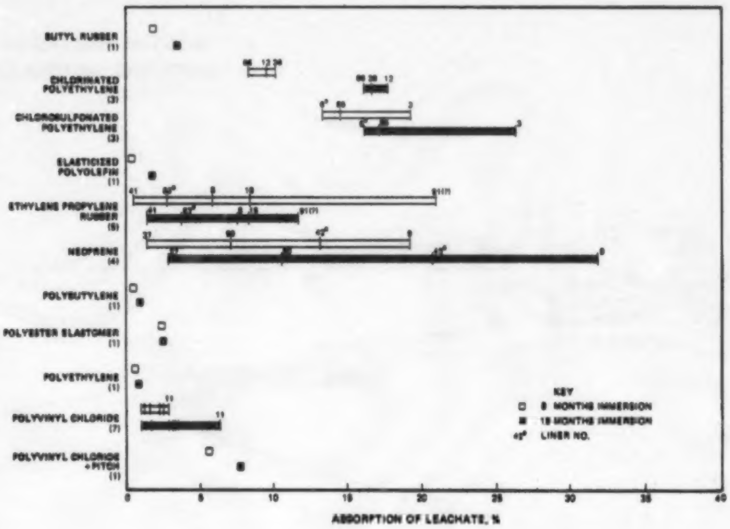

Figure 4-3 Swelling of membrane liners during immersion in leachate for 8 and 19 months. The number of different liners of a given polymer that are included in the test is shown in parentheses.

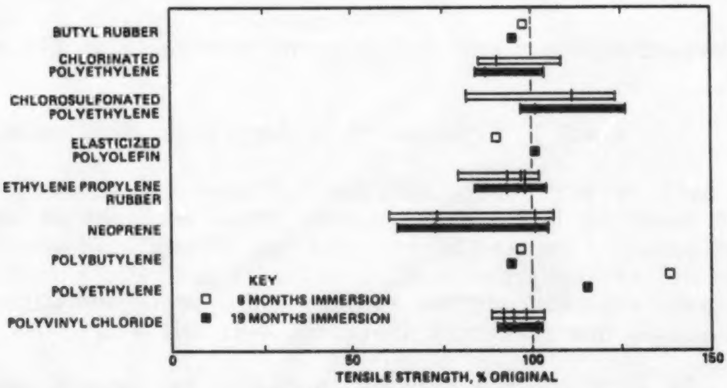

Figure 4-4 Retention of tensile strength of polymeric membrane liners on immersion in landfill leachate after 8 and 19 months. Tensile strength data were obtained by averaging the tests in machine and transverse directions.

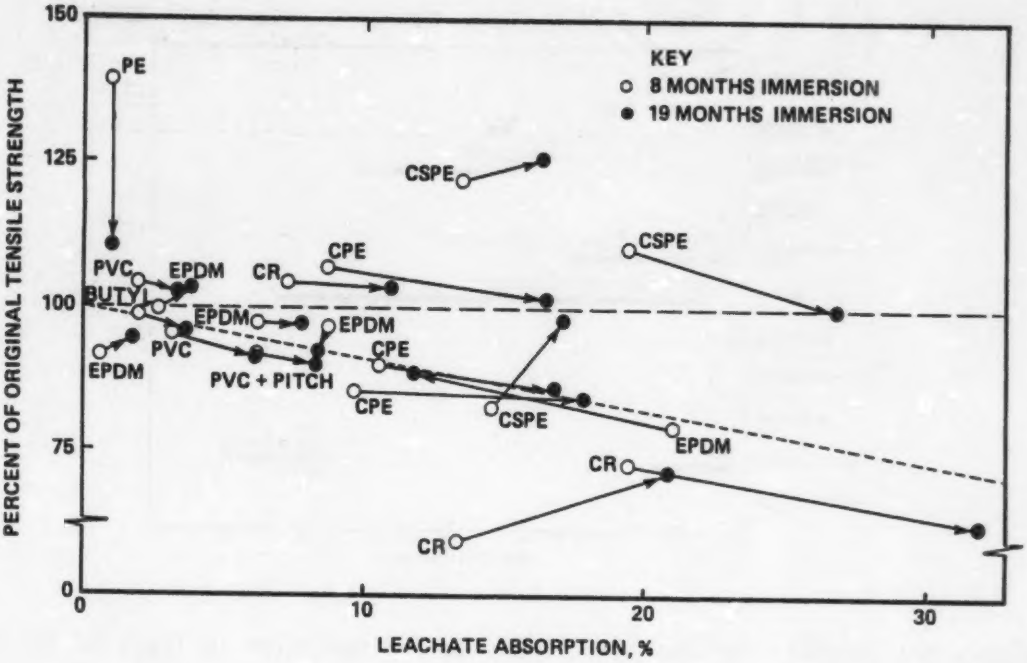

Figure 4-5 Retention of average tensile strength of membrane liner materials during immersion in landfill leachate as a function of swelling by the leachate.

Details regarding the other exposures are available in EPA reports. (Haxo, 1978 and 1980).

4.4.3.1 Exposure of Primary Liner Specimens

In this part of the study, specimens of one square foot of eight different polymeric membrane liners were exposed below one foot of waste in cells which simulated ponds. The wastes included two strong acid wastes, a strong alkali waste, an oil refinery tank bottom waste, a lead waste from gasoline, saturated and unsaturated hydrocarbon wastes, and a pesticide waste. Characteristics of these wastes are presented in Tables 4-11 and 4-12.

The exposure cell for the primary specimens is shown schematically in Figure 4-6. A similar type of exposure cell has been used for the thick admix and soil liners (Figure 4-7). Each membrane specimen was prepared with a field-type seam across the center made according to the recommended practice of the supplier of the membrane. Two specimens of each liner material were placed in two sets of cells which were loaded with portions of the same waste. The cells were dismantled at two exposure times and the liner specimens were recovered, analyzed, and their physical properties measured.

TABLE 4-11. WASTES IN EXPOSURE TESTS
Phases

Type of Waste	Name	Organic Phase I	Water Phase II	Solids Phase III
Acidic	"HFL"[a]	0	100	0
	"HNO_3, HF, HOAC"[b]	0	100	0
Alkaline	"Slopwater"[a]	0	100	0
	"Spent caustic"[b]	0	95.1	4.9
Lead	"Low lead gas washing"))Blend[b]	10.4	86.2	3.4
	"Gasoline washwater")	1.5?	89.1?	-
Oily	"Aromatic oil"[b]	100	0	0
	"Oil Pond 104"[b]	89.0	0	11.0
	"Weed oil"[a]	20.6	78.4	-
Pesticide	"Weed killer"[b]	0	99.5	0.5

[a] In immersion tests only.
[b] In both primary exposure and immersion tests.

TABLE 4-12. WASTES IN EXPOSURE TESTS
pH, Solids, and Lead

Type of waste	Name	pH Water phase	Solids, % Total	Solids, % Volatile	Lead, ppm
Acidic	"HFL"	4.8	2.48	0.9	-
	"HNO_3, HF, HOAC"	1.5	0.77	0.12	-
Alkaline	"Slopwater"	12.0	22.43	5.09	-
	"Spent caustic"	11.3	22.07	1.61	-
Lead	"Low lead gas washing"	7.2	1.52	0.53	34
	"Gasoline washwater"	7.9	0.32	0.17	11
Oil	"Aromatic oil"	-	-	-	-
	"Oil Pond 104"	-	ca. 36	ca. 31	-
	"Weed oil"	7.5	1.81	1.00	-
Pesticide	"Weed killer"	2.7	0.78	0.46	-

Source: Haxo, 1980a.

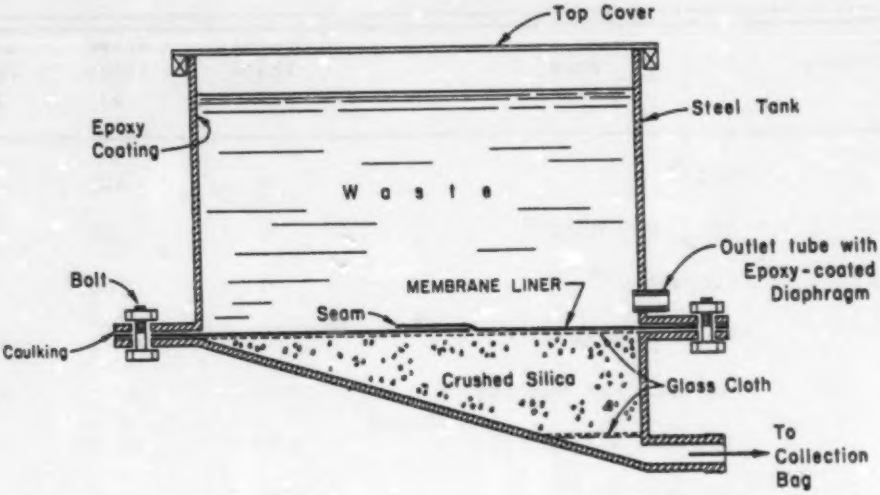
Top Cover
Steel Tank
Epoxy Coating
Waste
Outlet tube with Epoxy-coated Diaphragm
Bolt
MEMBRANE LINER
Seam
Caulking
Crushed Silica
Glass Cloth
To Collection Bag

Figure 4-6. Exposure cells for membrane liners. Dimensions of the steel tank are 10 x 15 x 13 inches in width, length, and height.

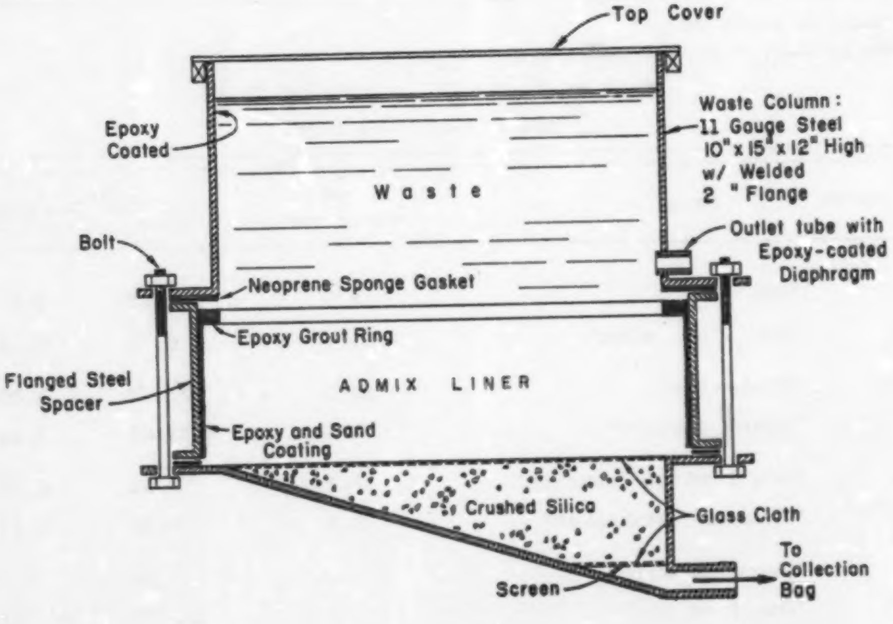
Top Cover
Epoxy Coated
Waste Column: 11 Gauge Steel 10" x 15" x 12" High w/ Welded 2 " Flange
Waste
Outlet tube with Epoxy-coated Diaphragm
Bolt
Neoprene Sponge Gasket
Epoxy Grout Ring
Flanged Steel Spacer
ADMIX LINER
Epoxy and Sand Coating
Crushed Silica
Glass Cloth
To Collection Bag
Screen

Figure 4-7. Exposure cell for thick liners.

The first set of primary specimens was removed after one year of exposure and the second set after approximately 3.5 years of exposure to the wastes. Selected data on the second set after 3.5 years of exposure are presented in Tables 4-13 and 4-14. Table 4-13 presents the results of tests for volatiles and extractables of the eight membrane liners exposed in four different wastes. The volatiles were determined on a sample of the liner immediately after removal from the waste and the extractables were determined on the specimen which had been devolatilized. Results show the variation in the volatiles and extractables both with respect to the polymer type and the waste. There are indications that, in some cases, the plasticizer which was in the original compound was removed during the exposure period. In other cases, the extractables were higher, indicating the absorption of nonvolatile constituents in the waste.

Table 4-14 presents the effects of one and three years of exposure upon ultimate elongation and S-100 modulus of the same liner materials in the same wastes.

The effects of 3.5 years of exposure to the wastes varies considerably with the liner material and the waste. Only one material, a polyester elastomer, completely lost its elongation and that was in exposure to a strongly acidic waste. The CSPE, neoprene, and EPDM liners lost significant elongation in the caustic, lead, and nitric acid wastes, respectively. The CSPE and PVC liners stiffened during exposure to the wastes and the neoprene liner softened.The CSPE crosslinked during exposure and the PVC probably lost plasticizer.

4.4.3.2 Immersion Tests

Concurrent with the exposure of the primary liners in the bases of the cells, supplemental membrane liner specimens were hung in the wastes. The effects of exposure were measured by determining the increase in weight, analyzing the exposed specimens and measuring selected physical properties. Details of the procedure followed in conducting the immersion tests are presented in Appendix III-A. The effects of the immersion tests on absorption of the wastes are shown in Table 4-15; the effects upon the elongation of the same materials are shown in Table 4-16.

In these tables, data are presented for 12 membranes based on eight different polymers immersed in eight different wastes from 2 to 2.2 years. Among these membrane specimens were two CSPE membranes, two EPDM membranes, and three PVC membranes. The oily type wastes, which included the lead waste, Oil 104, aromatic oil, and weed oil, represented a range in aromaticity and molecular weight. The weed oil, which is the most aggressive of the oils toward lining materials, is a light aromatic oil. It particularly swelled the CPE and CSPE liners. Oil 104 is a naphthenic and relatively heavy type of oil. It had its most pronounced effect upon the butyl rubber liner. In all cases, there was a variation between the two liners based upon the same polymer. The differences between the two CSPE specimens was the smallest. There were significant differences among the three PVC specimens. The effects of swelling carried into the elongation of the swollen material resulting, in some cases, in drastic reductions in this property.

TABLE 4-13. VOLATILES[a] AND EXTRACTABLES[b] OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS AFTER EXPOSURE TO SELECTED WASTES

Liner data		Compound data		Volatiles, % Waste and exposure time in days (d)					Extractables, % Waste and exposure time in days (d)			
Polymer	No.[c]	Type[d]	Extractables, %	Unexposed	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d
Butyl	57R	VZ	6.4	0.29	4.8	11.5	1.4	3.5	7.6	8.7	7.9	7.9
CPE	77	TP	9.1	0.00	7.9	13.2	2.8	19.2	9.4	10.6	9.1	7.2
CSPE	6R	TP	3.8	0.29	9.7	7.2	5.8	11.4	5.4	4.6	3.8	6.0
ELPO[e]	36	TP	5.5	0.15	...[f]	5.3	...[f]	1.5	...[f]	7.1	...[f]	8.1
EPDM	26	VZ	18.2	0.50	6.3	12.0[g]	1.3	5.3	25.2	22.8[g]	24.0	26.0
Neoprene	43	VZ	13.9	0.45	13.6	...	5.7	17.5	16.1	...	13.7	12.2
Polyester	75	TP	2.7	0.26	2.9	7.4[h]	0.9	1.7	5.8	13.5[h]	3.3	5.4
PVC	59	TP	35.9	0.26	3.6	...[f]	1.8	4.4	33.4	...[f]	35.6	22.5

[a] Percent weight loss after 2h @ 105°C.
[b] After devolatization in air oven for 2h @ 105°C.
[c] No. = Serial number of liner set by Matrecon; R = Reinforced with a fabric.
[d] Type = Vulcanized (VZ) or thermoplastic (TP).
[e] ELPO = Elasticized polyolefin.
[f] Specimens still under exposure to waste.
[g] Exposure time = 1150 days.
[h] Exposure time = 509 days.

Source: Haxo, 1980a.

TABLE 4-14. RETENTION OF ULTIMATE ELONGATION[a] AND S-100 MODULUS[b] OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS ON EXPOSURE TO SELECTED WASTES

Liner data		Compound data			Ultimate elongation, % retention Waste and exposure time in days					S-100 modulus, % retention Waste and exposure time in days			
Polymer	No.[c]	Type[d]	Extractables, %	Original elongation,[e] %	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d	Original S-100,[f] psi	Pesticide 1260 d	HNO_3 1220 d	Caustic 1250 d	Lead 1340 d
Butyl	57R	VZ	6.4	70	77	419	142	108	...	...	...	...	...
CPE	77	TP	9.1	405	90	88	115	84	900	114	84	132	72
CSPE	6R	TP	3.8	235	88	83	68	81	645	118	112	199	118
ELPO[g]	36	TP	5.5	665	...[h]	96	...[h]	106	875	...[h]	103	...[h]	110
EPDM	26	VZ	18.2	450	103	79[i]	95	106	360	88	70[i]	109	80
Neoprene	43	VZ	13.9	320	84	...	95	75	460	54	...	96	62
Polyester	75	TP	2.7	575	87	<1[e]	87	90	2585	96	...	110	88
PVC	59	TP	35.9	385	93	...[h]	95	106	960	144	...[h]	170	107

[a] Ultimate elongation = The average of the values in both machine and transverse directions.

[b] S-100 modulus = The average of the values in both machine and transverse directions of the stress at 100% elongation.

[c] No. = The serial number of liner set by Matrecon.

[d] Type = Vulcanized (VZ) or thermoplastic (TP).

[e] Original elongation = Ultimate elongation of unexposed material.

[f] Original S-100 = S-100 modulus of unexposed material.

[g] ELPO = Elasticized polyolefin.

[h] Specimens still under exposure to waste.

[i] Exposure time = 1150 days.

[j] Exposure time = 509 days.

Source: Haxo, 1980a.

TABLE 4-15. ABSORPTION OF WASTE BY POLYMERIC MEMBRANE ON IMMERSION IN SELECTED WASTES
(Data in Weight Percent)

		Data on liner compound		Waste and immersion time in days (d)							
Polymer	No.[a]	Type[b]	Extractables, %	Pesticide 807 d	HNO_3 751 d	HF 761 d	Spent caustic 780 d	Lead 786 d	Oil 104 752 d	Aromatic oil 761 d	Weed oil 809 d
Butyl	44	VZ	11.8	1.6	3.8	3.7	0.8	28.7	103.9	31.2	64.2
CPE	77	TP	9.1	12.7	19.9	12.9	1.1	118.9	36.9	226.4	ND[c]
CSPE	6R[d]	TP	3.8	17.3	10.0	9.0	4.3	120.7	49.5	105.2	368.4
CSPE	55	TP	4.1	15.7	10.9	7.7	3.3	116.2	55.0	110.5	347.5
ELPO[e]	36	TP	5.5	0.5	7.6	1.1	0.6	17.0	28.9	29.4	38.1
EPDM	83R[d]	TP	18.2	4.5	4.2	3.1	1.6	24.8	26.5	19.8	84.4
EPDM	91	VZ	23.6	20.4	50.9	23.9	1.3	34.7	84.7	34.2	76.2
Neoprene	90	VZ	21.5	11.4	17.4	12.0	1.5	59.1	26.3	142.6	89.3
Polyester	75	TP	2.7	4.2	6.4	2.0	1.5	7.4	8.5	16.6	14.7
PVC	11	TP	33.9	5.1	22.1	18.1	0.4	-1.5	-10.4	18.5	15.3
PVC	59	TP	35.9	1.0	-6.1	0.9	-0.9	7.4	-0.5	28.9	24.7
PVC	88	TP	33.9	1.6	28.2	14.3	1.1	-5.2	-9.8	14.1	25.2

[a] No. = the serial number of liner set by Matrecon.
[b] Type = vulcanized (VZ) or thermoplastic (TP).
[c] ND specimen was lost; some indication that it dissolved in the waste.
[d] R = fabric reinforced.
[e] ELPO = elasticized polyolefin.

TABLE 4-16. VOLATILES[a] CONTENT OF FLEXIBLE POLYMERIC LINERS ON IMMERSION IN SELECTED WASTES
(Data in percent loss of weight)

		Data on liner compound			Waste and immersion time in days (d)							
Polymer	No.[b]	Type[c]	Extractables, %	Volatiles (unexposed)[d], %	Pesticide 807 d	HNO_3 751 d	HF 761 d	Spent caustic 780 d	Lead 786 d	Oil 104 752 d	Aromatic oil 761 d	Weed oil 809 d
Butyl	44	VZ	11.8	0.28	3.0	3.8	2.9	6.9	15.3	9.8	3.3	19.2
CPE	77	TP	9.1	0.00	8.6	20.4	8.1	1.6	42.2	5.2	ND[e]	ND[f]
CSPE	6R[g]	TP	3.8	0.29	10.8	10.4	7.6	4.2	3.3	20.2	6.1	50.7
CSPE	55	TP	4.1	0.42	7.9	9.1	7.1	3.6	1.1	10.0	4.8	39.7
ELPO[h]	36	TP	5.5	0.15	0.45	7.2	1.3	0.6	9.5	3.1	1.5	16.4
EPDM	83R[g]	TP	18.2	0.31	4.89	3.1	2.8	2.2	13.9	8.5	4.4	24.1
EPDM	91	VZ	23.6	0.34	15.6	22.6	23.6	1.2	18.5	11.8	4.2	33.4
Neoprene	90	VZ	21.5	0.27	7.26	13.7	10.5	2.9	23.6	6.3	3.9	28.9
Polyester	75	TP	2.7	0.26	1.75	28.0	3.8	1.3	6.1	2.1	3.4	9.5
PVC	11	TP	33.9	0.15	30.9	22.6	18.3	0.6	16.1	2.7	3.6	17.1
PVC	59	TP	35.9	0.26	40.1	10.6	3.0	1.5	12.7	3.3	4.6	16.1
PVC	88	TP	33.9	0.17	3.51	23.2	13.1	1.2	11.5	4.3	3.5	24.1

[a] "Volatiles" content is the loss in weight of a specimen of liner (unexposed or exposed) on air-oven heating for 2 hours at 105°C.

[b] No. is the serial number of liner assigned by Matrecon for identification.

[c] Type of compounds: vulcanized (VZ) or thermoplastic (TP).

[d] Volatiles content of unexposed specimens of liners.

[e] ND = no data obtained because the sample was too badly deteriorated to test.

[f] Immersion sample was lost. Some indication that it dissolved in the waste.

[g] R = fabric reinforced.

[h] ELPO = elasticized polyolefin.

4.3.3.3 Pouch Test

A new test, which was devised during work on the two EPA research contracts, appears to be a promising method for assessing the permeability and durability of membrane liner materials in contact with wastes.

In this test, small pouches are fabricated of the membranes to be tested. They are filled with wastes or other test fluids such as salt water, sealed and immersed in deionized water. The permeabilities of the membranes to water and to pollutants are determined by observing, respectively, the change in weights of the bags and the measurements of pH and electrical conductivity of the deionized water. Due to osmosis, water should enter the pouch and ions and dissolved constituents should leave the bag. Details of the test procedure are presented in Appendix III-B. A schematic representation of the pouch test showing the movement of the various constituents in shown in Figure 4-8.

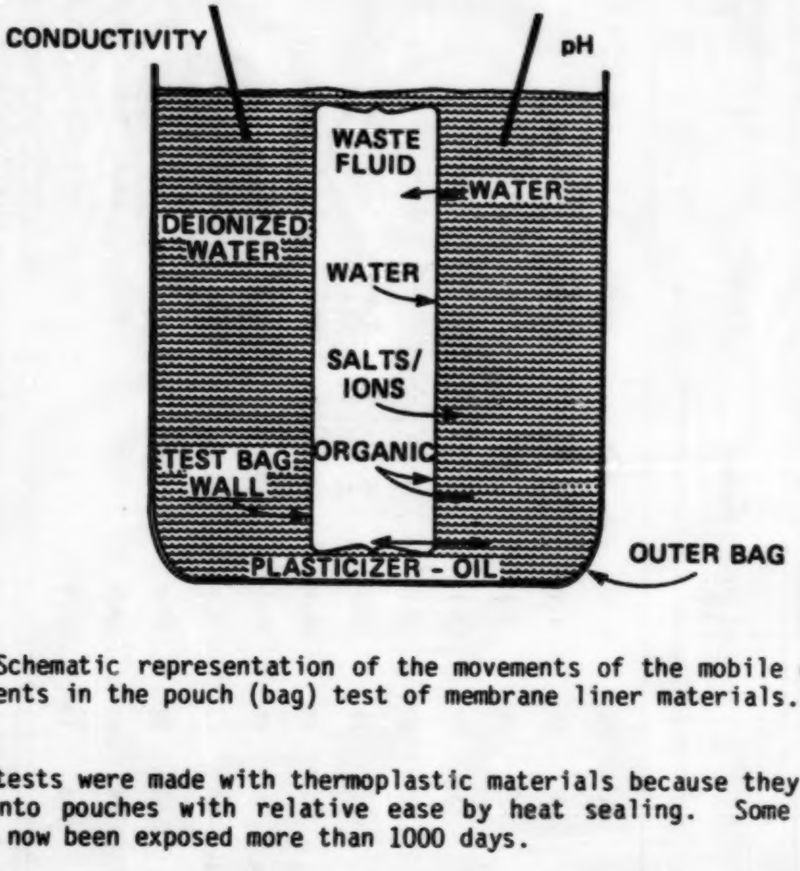

Figure 4-8. Schematic representation of the movements of the mobile constituents in the pouch (bag) test of membrane liner materials.

The initial tests were made with thermoplastic materials because they could be fabricated into pouches with relative ease by heat sealing. Some of these pouches have now been exposed more than 1000 days.

Bags containing the wastes actually increased in weight, indicating the flow of water into the bags through osmosis, as shown in Table 4-17. The long-term tests now show that some ionic material is diffusing through the liners into the deionized water.

TABLE 4-17. RELATIVE PERMEABILITIES OF POLYMERIC MEMBRANE LINING MATERIALS IN POUCH TEST WITH THREE WASTES[a]

Average flux into the pouch in grams per square meter per day x 10^{-2}

Polymer	Liner no[b]	Nominal thickness, mils	HNO_3 waste	Spent caustic	Slopwater
CPE	86	22	78.2	26.3	190.7[c]
CSPE	85	33	67.8	36.3	49.2
ELPO[d]	36	23	2.5	3.8	18.4[e]
PB[f]	98	7.5	3.0	7.9	13.6
PVC	19	22	32.4	78.8	325.0
PVC	88	20	64.2	65.9	118.8[g]

[a] Exposure time is 552 days unless otherwise noted.

[b] Matrecon identification number

[c] Pouch failed at 450 days.

[d] Elasticized polyolefin.

[e] Pouch failed at 300 days

[f] PB - polybutylene

[g] Pouch failed at 40 days

Table 4-18 presents the interpolated or estimated times to reach an electrical conductivity of 1000 μmho for slopwater and nitric acid, both of which are concentrated wastes. The data show the greater permeability of the PVC lining materials as compared to CPE, CSPE, elasticized polyolefin, and polybutylene; the latter two are partially crystalline materials.

TABLE 4-18. PERMEABILITY OF THERMOPLASTIC POLYMERIC MATERIALS IN OSMOTIC POUCH TEST

Time in days for electrical conductivity of water in outer pouch to reach 100 μmho

	Wall of inner bag			Waste in inner bag	
Polymer	Liner no[a]	thickness mils	Extractables, %	NHO_3 waste	Slopwater
CPE	86	20	...	200	420
CSPE	85	33	...	500	510
ELPO[b]	36	22	5.5	300	>1000
PB[c]	98	7	...	600	>1000
PVC	19	20	38.9	70	200
PVC	88	20	33.9	110	160

[a] Matrecon identification number

[b] Elasticized polyolefin.

[c] PB = polybutylene.

Table 4-19 presents the results of the thermoplastic membranes tested with 5% sodium chloride solution. The data again show the greater permeability of the PVC with respect to the CSPE and the elasticized polyolefin, which is the most impermeable of the three. These pouches have now been taken out of the test and physical properties of the pouch wall materials have been measured. The results show that, within the 1150 days of exposure, there was some loss in elongation and an increase in the stiffness of the membranes.

TABLE 4-19. POUCH TEST OF THERMOPLASTIC MEMBRANES[a]
Pouches filled with 5% NaCl solution

Polymer	CSPE	ELPO	PVC
Liner number[c]	6	36	59
Thickness, mils.	32	23	33
Volatiles content of exposed pouch wall, %	8.7	0.38	0.90
Change in weight of pouch plus waste, %	+2.6	+0.71	+0.38
Change in weight of fluid in pouch during exposure, %	+0.95	+0.76	+0.38
Conductivity of water in outer pouch, µmho	585	34	4500
Retention of physical properties, %:			
Elongation	95	100	94
S-100	106	119	120

[a] Exposure time 1150 days (164 weeks).

[b] Elasticized polyolefin.

[c] Matrecon identification number.

4.4.4 General Discussion of Results

The types of polymeric compounds that have been studied in the above two projects were described in Section 3.4.3. They are based upon the following four types of polymers:

- Vulcanized elastomers, e.g. butyl rubber, neoprene, EPDM, CSPE, CPE, ECO, nitrile rubber, blends.
- Thermoplastic elastomers (TPE), e.g. CSPE, CPE, polyolefins, blends.
- Thermoplastics, e.g. plasticized PVC, PVC blends with selected elastomers.
- Crystalline polymers (thermoplastic), e.g. LDPE AND HDPE.

Note: CSM is the identification used in the liner industry for chlorosulfonated polyethylene

Some of the polymers used in both crosslinked and thermoplastic versions. For example lining materials of CSPE and EPDM have been manufactured in both crosslinked and thermoplastic versions.

On exposure to fluids, most polymeric materials, whether they are crosslinked or not, will tend to swell and change in some properties. The major factors involved in the swelling of polymeric materials are:

- Solubility parameter.
- Crosslinking of polymer.
- Crystallinity of polymer.
- Chemical stability.
- Soluble constituents in compound.

The solubility parameter is used by polymer scientists to measure the similarity in chemical characteristics of the polymer such as is in the lining material, with a fluid with which it is in contact (Hilderbrand and Scott, 1950). For example, a hydrocarbon rubber like natural rubber will swell and dissolve in a hydrocarbon such as gasoline. On the other hand, a highly polar polymer, such as polyvinyl chloride or nitrile rubber, will not dissolve in gasoline.

Crosslinking a polymer or a rubber reduces its ability to swell in a solvent. Polymer scientists use the swelling of a crosslinked rubber as a measure of the degree of crosslinking: the greater the crosslinking, the less the swelling. This effect is pronounced in such rubbers as CSPE and CPE, liners of which are available in both vulcanized and unvulcanized forms.

Crystallinity of a polymer acts much like crosslinking to reduce the ability of a polymer to dissolve. Highly crystalline polymers, such as high-density polyethylene, will not dissolve in gasoline, even though they are basically similar in chemical composition. Such high density polymers are finding considerable use in containers for a wide range of solvents and chamicals.

Chemical stability means that the polymer does not degrade on aging which would result principally in reducing its molecular weight causing swelling and dissolving.

The soluble constituents of a rubber compound have a strong bearing on the ability of that material to swell. Most polymers contain minor amounts of solubles, e.g. salt, which are used in the manufacture of the raw rubber and of the compound. The swelling is a result of the diffusion of water into the compound. Soluble constituents can also arise from the compounding ingredients which are present in the compounding.

The effects that the first three factors have on the swelling of liner materials is illustrated in Figure 4-9. The swelling of the thermoplastic type of material in a fluid with which it is somewhat compatible is represented in Curve A, which indicates that the material will continue to swell with time and that no real plateau is reached.

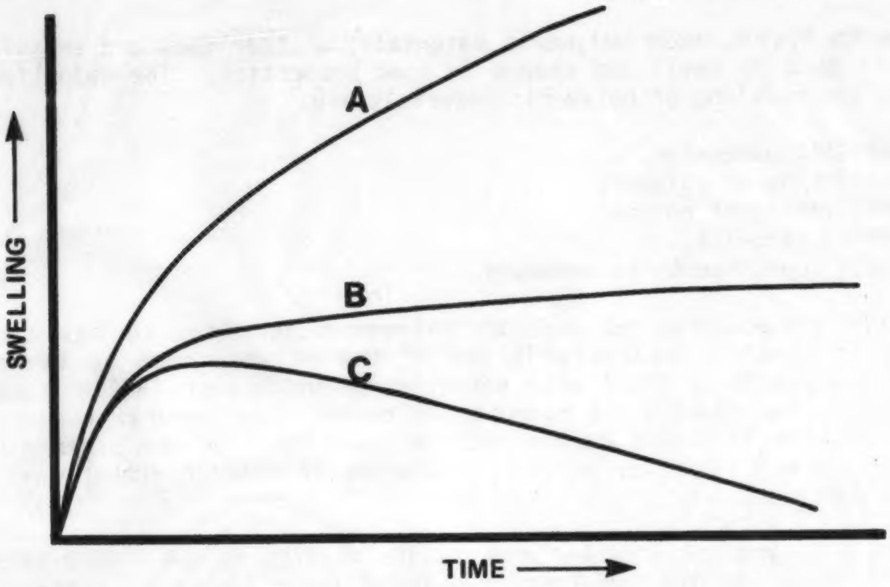

Figure 4-9. Types of swelling of polymeric membranes.

The swelling of crosslinked material is represented in Curve B, in which the swelling reaches a plateau and changes only slightly with time. The level of the plateau is determined by the degree of crosslinking and by the solubility parameter of the waste fluid and the polymer.

Curve C represents a plasticized thermoplastic or a oil-extended rubber in which the plasticizer is leached from the polymer. In this case, there is an initial swelling and reduction in swelling. In some cases, there can be a shrinkage of the liner due to the loss of plasticizer or oil. The effects on the physical properties of these exposures have been indicated in the above sections. The swelling will result principally in the softening of the material, possibly in its dissolving, and in increased permeability.

In selecting polymer and rubber compounds for service in a liquid medium, a designer generally selects materials which have low or negligible swell. Swelling of a compound usually has adverse effects which will make the product unserviceable. Some of the major effects of swelling generally are:

- Softening.
- Loss or tensile and mechanical strength.
- Loss of elongation.

- Increased permeability.
- Increased potential of creep.
- Greater susceptibility to polymer degradation.

All of these effects are adverse with respect to liner performance. Swelling, therefore, is a valuable indicator of the compatibility of a liner to a waste.

Shrinkage can also be a measure of compatibility for liner compositions that are highly plasticized. For example, in the case of highly plasticized PVC compounds, the plasticizer can leach and diffuse out of the polymer leaving the compound stiff and brittle.

4.5 Effect of Waste Fluids on Admix and Other Liner Materials

As a part of the two liner research programs described in the above section, a variety of soils and admix liner materials were exposed to the same waste fluids. The results of these tests, after limited exposure, are described in the next two subsectons.

4.5.1. Exposure to Municipal Solid Waste Leachate

After one year of exposure to leachate, the asphalt concrete and soil asphalt liners lost drastically in their compressive strengths; however, they maintained their impermeability to leachate. The asphalt binder, which normally hardens on aging in air, became softer indicating possible absorption of organic components from the leachate.

The soil cement liner lost some of its compressive strength; however, it hardened considerably during the exposure period and cored like a portland coment concrete. It became more impermeable during the exposure.

Inhomogeneities in the admix materials, which probably caused the leakage in the paving asphalt and soil asphalt liners, indicate the need for considerably thicker materials in practice. Thicknesses of two to four inches were selected for this experiment to give an accelerated test and were designed with an appropriately-sized aggregate. The same compositions in the second set of 12 liners did not leak after 27 months of exposure.

The asphalt membranes withstood the leachate for one year, although they did swell slightly. There was no indication of disintegration or dissolving of the asphalt.

4.5.2 Exposure to Hazardous Wastes

Five types of admix materials are being studied in this ongoing project:

- Compacted fine-grain native soil.
- Soil cement.

- Modified bentonite in sand.
- Hydraulic asphalt concrete.
- Membrane based on emulsified asphalt on a nonwoven fabric.

Because of the incompatibility of some of the wastes with particular admix materials, several combinations were deleted. The only liner material that was placed below the acid waste was the hydraulic asphalt concrete. Neither of the two oily wastes was placed on the asphaltic liners; however, the lead waste, which contained a light, oily fraction, was placed on these liners. The performance of the individual admix liners is discussed below:

Compacted fine-grain soil - All of the wastes, except the nitric acid waste, were placed above the compacted fine-grain soil liner. Seepage below all of the liners took place. The amount of seepage was measured and the respective pH, conductivity, and percent total solids were determined. The following observations are made with respect to the seepages through the soil liners:

a. The rate of seepage is 10^{-8} to 10^{-7} cm sec^{-1} which compares favorably with the permeability of the soil measured in the laboratory permeameter. There is some variation in the amount of seepage collected below the liner which may reflect permeability differences, perhaps due to density of the soil.

b. The fluids being collected after more than three years of exposure still continue to be essentially neutral and to have high solids content (mostly salt) and electrical conductivity.

c. There is a downward trend in solids content of the seepages collected under the pesticide and lead wastes, but the seepage under the spent caustic waste continues to be 23% solids.

One set of the soil liners was removed and tested. The permeability of a specimen taken from the cell containing the soil and the aromatic oil waste was determined using a "back-pressure" permeameter (Vallerga and Hicks, 1968). The sample was collected from a depth of seven to ten inches below the surface of the soil, i.e. from that part of the soil which was not penetrated by the oil. The three consecutive values obtained were: 1.83×10^{-8}, 2.43×10^{-8}, and 2.60×10^{-8} cm sec^{-1}. These figures indicate the low permeability of the soil, which had a bulk density of 1.318 g cm^{-3} and a saturation degree of 101%.

Analyses for trace metals were made of the soils which were below the lead waste, Oil 104, and the aromatic oil. The testing included determination of pH and heavy metal content (cadmium, chromium, copper, magnesium, nickel, and lead) on samples collected at different depths in the cells.

With the exception of the liner exposed to spent caustic, the pH of the soil liner was not significantly altered by the wastes. The pH of these samples was in the range of 7.0 to 7.6; the ratio, soil:solution, was 1:2 with 0.01 N $CaCl_2$ being the equilibration solution.

In the case of the spent caustic, the pH values were around 9.0 for samples collected in the first two to three centimeters, which concurs with our previous findings that, over the exposure period of 30 months, the wetting front of the wastes penetrated the soil to a depth of only three to five centimeters.

The heavy metals distribution, as indicated by the analysis, shows, in the case of the lead, only a shallow contamination of the soil. Similar results were obtained on all six heavy metals in the case of the soil below the Oil 104 waste.

Soil cement - All of the wastes except the acid waste were placed on the soil cement liner. No seepage occurred through the liner during the 30 months of exposure.

One set of the soil cement lining materials was recovered after 625 days of exposure to the various wastes and the individual linings were cored and tested for compressive strength. In all cases, compressive strength of the exposed soil cement was greater than that of the unexposed material. There was some blistering of the epoxy asphalt coating which was applied to one-half the surface of each specimen.

Modified Bentonite and Sand - Two types of modified bentonites were used as liners in ten cells. One type allowed somewhat less seepage than the other. There was measurable seepage in seven of the ten cells and one failed allowing the waste (Oil 104) to come through the liner.

Irrespective of the type of waste above the liner, the quality of the seepage was not greatly different among the samples collected. The seepages collected below the pesticide waste on both types of modified bentonite liners were similar.

When the spacers containing the bentonite-sand were sampled, it was found that there had been considerable channeling of the wastes into these liners. There was no channeling at the walls of the spacers.

This type of liner is probably not satisfactory for these types of waste. The use of a soil cover on the bentonite layer to produce an overburden would probably reduce the channeling effect.

Hydraulic Asphalt Concrete - Liner specimens of hydraulic asphalt concrete were placed under four of the wastes. Excluded were the oily wastes.

This lining material functioned satisfactorily under the pesticide and spent caustic wastes, but failed beneath the nitric acid waste. However, the failure arose primarily from the failure of the aggregate which contained calcium carbonate; also, the asphalt was hardened considerably.

In the case of the lead waste, the asphalt absorbed much of the oily constituents of the waste and became "mushy". There was some staining of the gravel below the asphalt liner.

Duplicate cells containing the hydraulic asphalt concrete and the lead waste are still functioning without seepage.

Membrane Based on Emulsified Asphalt and Nonwoven Fabric - This membrane was placed under only three of the six wastes: pesticide, spent caustic, and lead. The acid waste was excluded because of the severe hardening it caused the asphalt, and the oil wastes were excluded because of the high mutual solubility of the asphalt and the wastes.

The asphalt membrane functioned satisfactorily with the pesticide and spent caustic wastes; however, when the cell containing the lead waste was dismantled, the gravel below the liner was wet and stained brown. This result indicates that some seepage took place.

4.6 Compatibility of Liner Materials in Waste Fluids

4.6.1 Introduction

In Chapter 2 various wastes which must be contained are discussed with particular reference to their aggressiveness to various lining materials. In Chapter 3, various liner materials which are candidates for the lining of waste disposal facilities are described and discussed with respect to their composition and characteristics.

The compatibility of a liner with specific waste is on of the first considerations that a designer has in planning a specific landfill site. The designer of a lined waste disposal site must decide which liner material of those he has available can effectively contain the particular waste over the needed length of time. In some cases, the requirement will be for extended lengths of time, such as would be encountered in landfills. The designer must determine what liner materials are compatible with the wastes that must be contained.

It is the objective of this section to summarize some of the information on the wastes and the liners presented in Chapters 2 and 3 and to describe the approach and methodology of determining the compatibility of liners with given wastes.

4.6.2 Screening of Liner Materials Based upon the State-of-the-art Knowledge

Although the direct experience of compatibility of liners and wastes based upon actual experience is limited, there is a vast amount of information available from the chemical and petroleum industries, soils science, materials science, polymer science and technology, containers industry, coatings industry, etc., from which the engineer and designer can draw to assess compatibility of given materials with wastes. The technology involving the use of materials for the lining of waste disposal facilities is relatively new. It must depend on the experience of other technologies while it is developing and obtaining experience.

In this section the initial screening of liners based upon the available knowledge is described.

4.6.2.1 Characterizing the Waste

As has been indicated in Chapter 2, the waste fluids that are in the waste or are leached from the waste can be highly complex materials usually containing water and a wide range of inorganic and organic dissolved constituents. Individually, most of the constituents are well characterized. The difficulty with waste fluids is that they are complex blends containing components that can be toxic and also affect lining materials in a variety of ways. Also, the waste fluid can be highly concentrated and relatively simple, such as would occur in a spill. The analytical capabilities have developed greatly in recent years, therefore, an accurate compositional analysis can generally be made of a waste fluid. The designer must characterize the waste by obtaining an analysis to determine its major constituents. With these data he can make a first estimate of the kind of a liner which must be avoided. For example, oily wastes generally degrade asphalts and many polymeric materials. Soils, though very effective with water, may interact with ionic components such as calcium or, in some cases, some of the organic solvents.

The characterization of the waste should focus on those waste properties which are potentially damaging to liners described in this study. The following is a partial listing of waste constituents which can adversely affect one or more of the liners:

- High pH, greater than 10.
- Low pH, lower than 3.5.
- Oily wastes.
- High temperature.
- Presence of exchangeable ions, e.g. calcium.
- Organic fluids and acids.
- Organic compounds, in general.

4.6.2.2 Characterizing the Liner Materials Available

As discussed in Chapter 3, the range of materials which could be used to line disposal sites is large and covers a wide range of types, from soils and admixes to membranes of many kinds. As the soil at the site would probably be a candidate liner, it should be thoroughly investigated with respect to its character, not only as to permeability, but also to compatibility with the waste that might be placed on it.

The effects of various salts and chemicals upon soils are known from the agricultural science and, to some extent, from chemical science. From the polymer industry there is considerable information available on the use of polymeric materials for the lining of many pipes, reactors, gaskets, etc. which function in non aqueous media, acids, bases, etc. Generally, these fluids are simple, that is the number of constituents are few. However, there is wide experience with handling these various materials. Many of these plastics and rubbers are used in outdoor applications and much information is available on their durability and weatherability. Considering the available liner materials, it is quite possible that some can be eliminated when considering the waste that must be contained.

4.6.2.3 Matrix of Liner Materials-Waste Compatibilities

Out of experience to date, matrixes of wastes and liners can be considered to indicate the general compatibility of some of the materials. An example of this is in Table 4-20 which shows the range of types of liner materials and a variety of industrial and hazardous wastes. In all cases, neither the types of liner materials nor the types of wastes are specific. Each has a range of compositions and characteristics. A rating of "good" indicates that the combination is probably satisfactory; "fair" indicates the combination should be tested, and "poor" indicates the combination should be avoided. This table functions only as an initial guide and, in many cases, specific combinations of liner materials and wastes must be tested before selecting acceptable liner materials. This is the subject of the next section.

4.6.3. Testing of Specific Combinations of Liners and Wastes

As indicated in the previous section, knowledge of the wastes to be contained and the lining materials available can be used to make an initial screening of specific lining materials which might be suitable for containing the wastes. In some cases this knowledge may be sufficient to make a choice, particularly if the waste does not contain components aggressive toward liners. Generally, a compatibility test should be performed before a specific liner is selected.

4.6.3.1 Sampling and Analyses of Wastes for Compatibility Tests

In order to run accurate compatibility tests of lining materials, a representative sample of the waste must be obtained. In as much as wastes are generally highly complex and heterogeneous, there is a major problem in obtaining representative samples. In some cases samples of the specific waste may not be available and similar types of wastes must be used. Furthermore, consideration must be given to the fact that over the period of time that an impoundment may be operating, there may be a change in the composition of the wastes.

4.6.3.2 Compatibility Testing of Soils

In Section 4.2 some of the testing of the soils which is necessary to determine the chemical sensitivity of the soil is described. The use of Atterberg limits using the wastes as the fluid, when compared with the use of water, will give an indication of the sensitivity of that soil. Also, the effect of the waste upon permeability of soils is described in Section 4.2 and Appendix III-D.

TABLE 4-20. LINER-INDUSTRIAL WASTE COMPATIBILITIES[a]

Liner material	Caustic petroleum sludge	Acidic steel-pickling waste	Electro-plating sludge	Toxic pesticide formula-tions	Oil refinery sludge	Toxic pharma-ceutical waste	Rubber and plastic
Soils:							
Compacted clayey soils	P	P	P	G	G	G	G
Soil-bentonite	P	P	P	G	G	G	G
Admixes:							
Asphalt-concrete	F	F	F	F	P	F	G
Asphalt-membrane	F	F	F	F	P	F	G
Soil asphalt	F	P	P	F	P	F	G
Soil cement	F	P	P	G	G	G	G
Polymeric membranes:							
Butyl rubber	G	G	G	F	P	F	G
Chlorinated polyethylene	G	F	F	F	P	F	G
Chlorosulfonated poly-ethylene	G	G	G	F	P	F	G
Ethylene propylene rubber	G	G	G	F	P	F	G
Polyethylene (low density)	G	F	F	G	F	G	G
Polyvinyl chloride	G	F	F	G	G	G	G

[a] Stewart, 1978. G = Good, F = Fair, P = Poor.

4.6.3.3 Polymeric Materials

Three individual types of tests have been found useful in assessing the effects of the wastes upon lining materials. These are:

- Immersion Test
- Pouch Test
- Tub Test

Each of these tests is described in detail in Appendix III-A, III-B, and III-C, respectively.

Immersion Test - In this test samples of the specific membrane liners are immersed in the waste and the effects of the immersion upon the weight and dimensions of the liner specimens and a selected number of physical properties are measured as a function of immersion time. By immersing the samples totally in the waste fluid, a somewhat accelerated test is generated. Further acceleration can be effected by increasing the temperature somewhat. However, the closer the temperature and exposure conditions are to actual service, the more reliable the results will be. Also, the longer the test can be run, the more reliable it will be. These types of tests should be initiated early in the design phase of the waste facility. An exposure period of twelve months is desirable. Samples can be withdrawn at one, two, four, etc., months to assess the effect as a function of time.

Pouch Test - This test was designed to measure the permeability of polymeric membrane liner materials to water and to dissolved constituents of the wastes. A sample of the waste is sealed in a small pouch fabricated of the liner material under test which is then placed in distilled or deionized water. Measurements are taken periodically to determine the extent of movement of water into the membrane and/or leakage of waste into the water. A concentration gradient is created by the deionized water on one side of the membrane and the waste on the other side. This test environment results in the movement by osmosis of water and ions and other dissolved constituents through the membrane due to the differences in concentrations on either side of the membrane. Changes in liner materials are observed and later physical properties are tested.

Tub Test - The purpose of this test is to evaluate flexible membrane liner materials under conditions which simulate those that occur in actual service. The effects of exposure to the sun, temperature changes, ozone, and other weather factors can be evaluated as well as the effect of a given waste on a specific liner. The fluctuation of the level of the waste is particularly significant in that a horizontal section of the liner is subjected to the effects of both the waste and weather. This alternating of conditions is especially harsh on liner materials and is usually encountered in the field.

4.7 Failure Mechanisms and Estimating Service Lives

An important factor in selecting liner material for a given disposal facility is to match the required life of the waste impoundment with the estimated service life that can be anticipated for a given liner in the particular exposure condition. It is recognized that there can be a range in the lives that are needed. For ultimate disposal of a waste, very long times are required during which a liner must maintain its integrity and function as designed. On the other hand, for temporary holding ponds, much shorter lives are satisfactory. Furthermore, the life of a liner will depend upon the waste which it contains.

In order to make estimates of the service lives, it is necessary to know how the liner system might fail. In Section 4.3 the various failure mechanisms relating to clayey soil liners are described and discussed. The effects of a variety of wastes on soils are described with particular reference to their loss in permeability and in strength resulting from the effects of chemical species on the soils.

The effects of various wastes on polymeric membrane and admix liner materials are described in Sections 4.4 and 4.5 respectively. Some of the effects appear to be severe enough to cause a liner to fail if the exposure is sufficiently long.

The experience in the field with membrane type liners and liners in general has been primarily for reservoirs and other water containment facilities. The failure type mechanisms that have been encountered are described by Kays (1977). An amplification of the subject of failure mechanisms and estimating service life will be forthcoming in revisions of this Manual.

This section describes and discusses the categories and characteristics of the failures of liners in the service environment. The objective of this section is to enable the user of this manual to understand and identify liner failures and the events leading to failure. The three major categories of liner failure that will be discussed in this subsection are physical, biological, and chemical. Table 4-21 is a listing of the principal failure mechanisims in liners.

Failure of liners include problems in the subgrade, the lining material itself, forces of weather and aging, and problems imposed by operating procedures on condition. The problems in subgrades are related to compaction, differential settling, slope sloughing, built-up hydrostatic and gas pressures. Failures may be induced by chemical and/or physical circumstances. Chemical compatibility failures are a function of the waste-liner combination, while physical failures are more often subgrade related.

4.7.1 Physical Failures

There are several modes of liner failure due to physical processes and stresses, each of which is described in the following paragraphs. Each particular failure mode may or may not apply to every type of liner. However, notable examples will be presented where warranted.

TABLE 4-21. FAILURE CATEGORIES

Physical	Biological	Chemical
Puncture	Microbial attack	Ultraviolet attack
Tear		Ozone attack
Creep		Hydrolysis
Freeze-thaw cracking		Ionic species attack
Wet-dry cracking		Extraction
Differential settling		Ionic species incompatibility
Thermal stress		Solvents
Hydrostatic pressure		
Abrasion		

4.7.1.1 Puncture

Puncture failure would most commonly occur in membrane liners; however, such failure can occur in the other types of liners under specific circumstances. Puncture failure of membrane liners due to sharp angular rocks in the subgrade that have become exposed to the liner because soil fines migrated downward over time is a major concern. Puncture from operations, man or vehicular, is of concern but can largely be mitigated through good operation procedures. Burrowing animals and amnimals seeking water can also cause puncture.

4.7.1.2 Tear

Tear failure is similar to puncture failure in its occurrence. Because of a membrane's relative thinness compared to soils, clays, asphalts and other liners, its resistance to failure in that dimension is correspondingly reduced. Localized structural tear failure can result from several stress-relaxation-stress cycles in which the liner is losing strength or it stretched with each cycle. Tear, like puncture, can occur due to operations or animals.

4.7.1.3 Creep

Creep is the common term used to describe increasing deformation of a material under sustained load. The main factors which influence creep failure are material microstructure, stress level and temperature. The significance of this type of failure is that it is difficult to detect and control. Creep can occur with any liner material.

4.7.1.4 Freeze-thaw Cracking

Cycles of freezing and thawing cause material cracking which leads to failure by volume expansion of liquids in pore spaces during freezing. This expansion increases pore space volume and the accessibility of liquids to the pore space volumes. In addition, the freeze-thaw cycle will not be a localized failure at a facility, but will occur throughout. Proper planning and design is essential to mitigate this type of failure in areas where freezing is a major concern.

4.7.1.5 Wet-dry Cracking

This mode of failure is most commonly found when clay liners are used. The wet-dry cycles cause alternate expansion and shrinkage of clay liners which decrease the strength of the liner and increase its overall effective permeability. Because soil materials have poor tensile strength, the shrinkage caused by drying is highly disruptive to the cohesive structure of clays. Other liners are adversely affected by wet-dry cracking, but to a lesser extent.

4.7.1.6 Differential Settling

Differential settling can damage all liners. This problem is best mitigated with a thorough geologic analysis prior to site selection and careful subgrade design and construction. Differential settling is a localized structural stress phenomenon and the greater the thickness and elasticity of the liner, the greater the tolerance range for differential settlement.

4.7.1.7 Thermal Stress

Thermal stress results from differential temperatures through a material or when temperature change is sufficent to cause a phase change in a material. This temperature change (especially in polymeric membranes) can cause volume changes by thermal expansion (or contraction) as the case may be, or by phase changes. Thermal stress may also become significant in light of the different reaction rates produced by individual components of a composite material. Phase changes in solid materials caused by heat, generally cause stress because different phases usually have different volumes per unit weight. Thermal stress can be controlled or tolerated by allowing for expansion or contraction in design, stress relief, or an acceptable range of variation. However, if the stress is great enough, cracks will occur. All asphalt liners are highly susceptible to temperature. Polymeric membrane liners are also temperature sensitive, but to a lesser degree.

4.7.1.8 Hydrostatic Pressure

Hydrostatic pressure is of concern when the structural support of a subgrade or base material is lost by piping, sinkholes, oxidation of organic material, settlement, etc. The effect of hydrostatic pressure exerted beneath a liner, which is due to inadequate drainage below the liner, is discussed in Chapter 5.

4.7.1.9 Abrasion

The continuous or near continuous action of abrasion on a liner has a significant wearing effect over time. Windborne abrasion is a serious consideration. In arid regions, sand particles carried by the wind have a sandblasting effect on the liner. Liners with high abrasion resistance must be specified, or a protective cover must be placed on the exposed berms. Runoff entering the pond from the surrounding topography may contain sticks, branches, rocks, and other debris which could abrade, tear, or even puncture the liner. Construction of a diversion channel to handle runoff will avoid the potential problems.

4.7.2 Biological Failures

The major emphasis on biologically induced failure is microbial attack in which the microbes "eat" the material and damage or destroy its structural integrity and low seepage characteristics. Particularly susceptible to biological attack are the plasticizers that are used in some polymer compounds. Bactericides are sometimes used to counteract this type of failure.

4.7.3 Chemical Failure

Because organic and inorganic chemicals constitute a great majority of the hazardous wastes to be contained in lined waste impoundment facilities, chemical failures are of great importance and significance. The following paragraphs describe the various types of chemical failure.

4.7.3.1 Swelling

The most serious chemical effect to polymeric liners at waste disposal facilities is that of swelling which is discussed in detail in Section 4.4.4. Potentially, sufficient swelling can cause loss in strength, elongation, creep and flow, and loss in puncture resistance. Failures of these types are most apparent when the liner is in direct contact with the wastes.

4.7.3.2 Extraction

Liner materials such as polyvinyl chloride which contain large amounts of monomeric plasticizer are highly susceptible to extraction of the plasticizer. Such extraction can result in embrittlement and shrinkage and possibly breakage of the liner. This effect is also discussed in Section 4.4.4.

4.7.3.3 Outdoor Exposure

Exposed polymeric linings can be subject to failure from heat and infrared, ultraviolet light, oxygen, ozone, and moisture. The factors generally operate in combination, with the presence of oxygen and moisture being the major contributing factors. Failure of the liner generally occcurs from embrittlement, shrinkage and breakage. Ozone can cause cracking of many polymers, particularly those which contain some unsaturation. Failures of this type occur in areas where the rubber sheeting is stretched.

Considerable information is available on the durability and service lives of exposed lining materials in which the principal environmental conditions are ultraviolet light, oxygen, ozone, heat, and wind (Strong, 1980).

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CHAPTER 5. DESIGN AND CONSTRUCTION OF LINED WASTE FACILITIES

5.1 Introduction

This chapter discusses the planning, design, and construction of lined facilities for waste storage and impoundment with particular regard to the design and construction of the lining. The discussion in this chapter provides site selection background, even though it is assumed that the site has been selected, and brings to the design and construction the guidelines of the best available engineering practice in liner technology. A detailed description of the installation of flexible membrane liners and the leachate collection systems is presented in Appendixes IV and V, respectively.

A critical aspect of each liner installation is adequate quality control of materials and workmanship. Ideally, the quality control function would be performed for the owner by a party independent of the liner manufacturer, fabricator, installer, and earthwork contractor. That party should be be responsible only to the owner of the facility. The owner should then be able to certify to a regulatory agency that the facility was constructed as planned. Often a quality control function is not included as part of a design and construction program. As a minimum, the owner or person ultimately responsible for the operation of the lined facility must check the quality of the materials and installation workmanship on the job site before accepting the finished product.

In this chapter the design and construction of liners of the following materials will be described:

a. soils and clays

b. admixed materials

c. flexible membranes

d. sprayed-on, soil sealant, and chemisorptive materials.

The design and construction of the final covers is discussed in a separate Technical Resource Document.

Lined impoundments have several specific end uses, each with its own particular objectives and period of performance. A lined waste impoundment can be a pond, a landfill for hazardous waste, or a sanitary landfill. The reasons for the use of a liner or liners range from groundwater protection to resource recovery to improved reliability. Depending upon the type(s) of waste, the period of containment, the surrounding climatic conditions, the available native soil and geologic structure, the geohydrologic characteristics, and several other factors, the selection, design, and construction of a lined waste impoundment can easily become a complex and intricate procedure. The waste characteristics significantly influence the choice of liner type, as does the purpose of the containment. If the facility is short term or temporary in its function, i.e. the waste is to be stored for a period of time and then excavated or transferred elsewhere, the selected liner component will be quite different from a facility which is proposed for permanent disposal of waste.

5.1.1 Types of Constructed Impoundments

The three major categories of new impoundment installations are as follows: (1) totally excavated; (2) filled; and (3) combination. Excavated impoundments are those which are dug from a surface (Figure 5-1) such that the major portion of the capacity is below the grade of the surrounding land surface. Filled impoundments are built up above grade such that the large majority of the capacity is at an elevation higher than the immediate surroundings. Combination impoundments result when material is both excavated and filled (Figure 5-2).

Excavated impoundments are found primarily in relatively flat areas where loose soil of a suitable nature (alluvium, for example) exists. As soil is excavated, some may be left at the perimeter of the excavation to be used for berm construction and levelling. The remainder of the material may be used for daily cover if the impoundment is a municipal solid waste landfill, for general grading, or for fill in other construction activities.

In some instances, bedrock is encountered before excavation of the impoundment is completed, thus necessitating blasting and rock removal. The economics of storage, containment, land, excavation difficulty, material use, and other considerations must be systematically analyzed before selecting the overall impoundment design.

Filled impoundments are frequently constructed at sites with bedrock near or at the surface because the cost of blasting and excavating precludes excavated impoundments in all but extreme cases. Frequently, where local geologic considerations preclude the economical construction of excavated impoundments, the desirable earth materials (sand, silt or clay) for berm and bottom construction are hauled in from off-site locations. A special type of filled impoundment is one built in an existing valley. An earthen dike is constructed between the valley walls and across the valley floor (Figure 5-3). Earth materials are used to prepare the sides and bottoms of the impoundment prior to liner installation. Care must be taken in valley span facilities to account for both surface and subsurface runoff and take appropriate measures to manage the flow.

Most impoundments can be classified as combination excavation-fill impoundments. A balanced cut-fill project will usually result in the best economics. The designer should recognize that the upper 3 to 12 inches of topsoil should

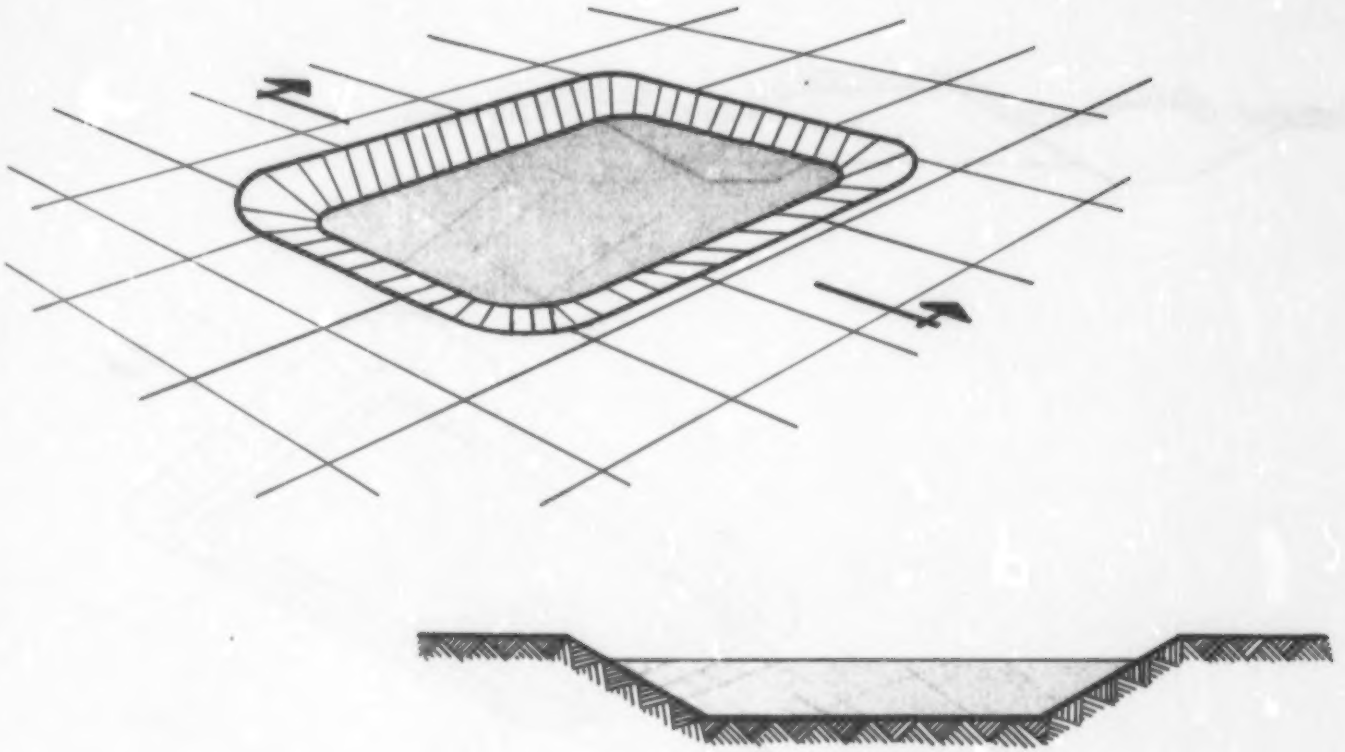


Figure 5-1. An excavated impoundment (Duvel, 1979).

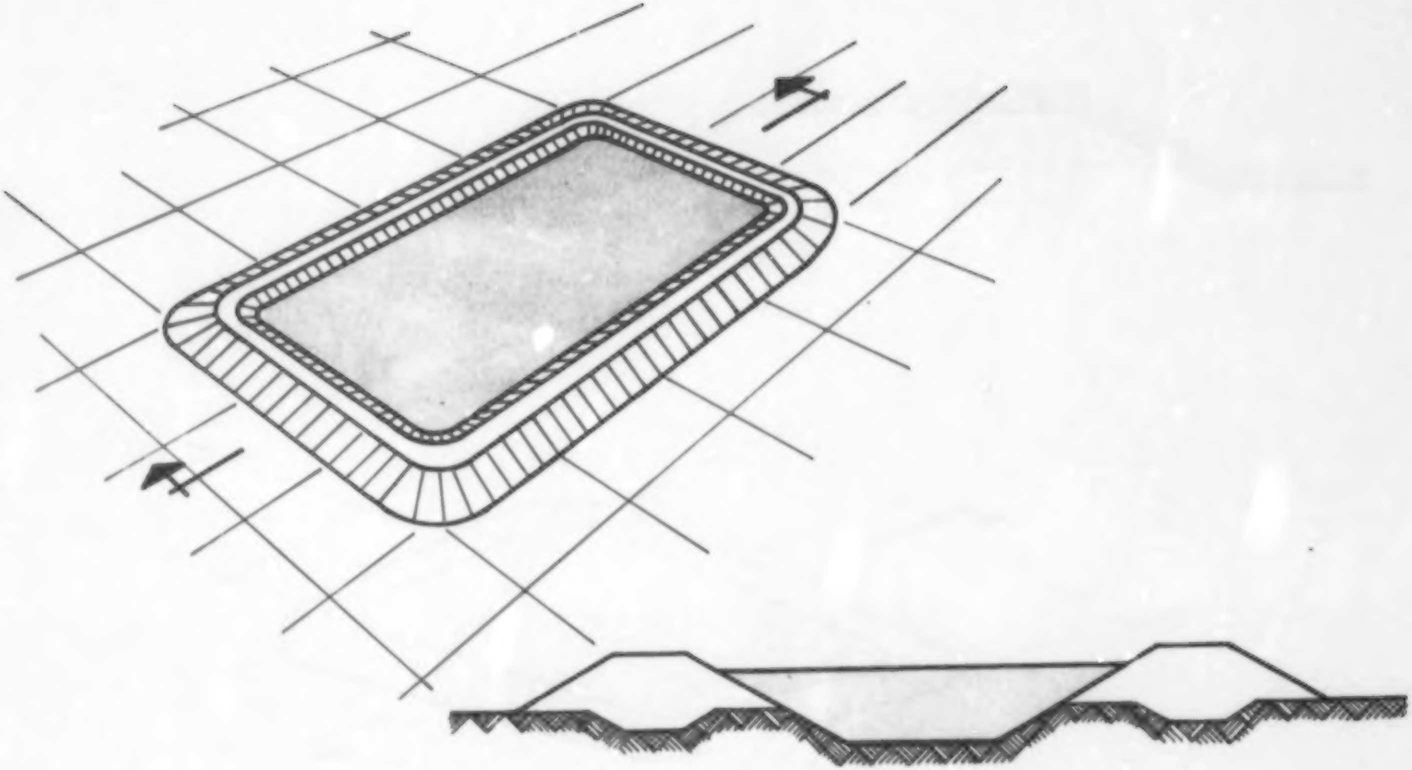


Figure 5-2. Diked pond partially excavated below grade (Duvel, 1979).

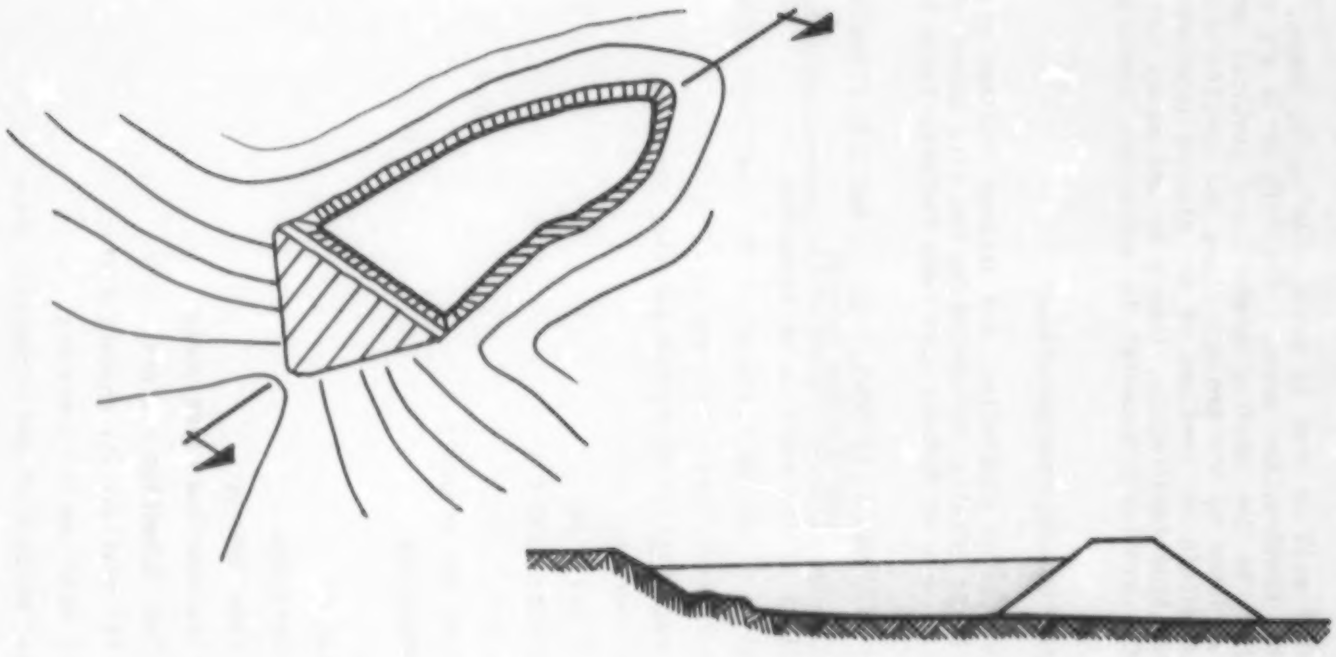


Figure 5-3. A cross-valley pond configuration (Duvel, 1979).

be removed for use elsewhere and that the soil excavated may shrink 5 to 20 percent between excavation and placement in an engineered fill.

The excavated material will be used to build side walls, berms, basal areas, and for miscellaneous construction needs. The fill soils are molded by the engineering contractor to the desired grades, and physical and mechanical characteristics established by the project plans and specifications. If the material at the site within the confines of the planned impoundment meets the needed design/construction constraints, then time and money can be saved by using the immediately available material in subsequent construction activities.

5.1.2 Site Planning Considerations

The construction, successful completion, and desired finished characteristics of an impoundment can be greatly influenced by the site chosen for its location. The selection of a site depends upon many factors. Table 5-1 is a list

TABLE 5-1. FACTORS TO BE CONSIDERED IN THE SITE PLANNING/ CONSTRUCTION PROCESS

Characteristics of the waste to be impounded
Characteristics (type and texture) of "in situ" soil materials
Subgrade characteristics - soil borings
Desired characteristics of bottom and side surfaces
Location of bedrock
Stability of materials
Drainage considerations
Impoundment dimensions
Wind direction and velocity
Ambient temperature
Gas venting
Local vegetation
Floor considerations
Berm width requirements
Inflow/outflow/overflow conveyances
Monitoring/leak detection systems
Cover material availability/characteristics
Proximity to major waste generators
Proximity to residential and commercial areas
Coupon testing and evaluation, if applicable
Weed control

of factors which should be considered in the site planning/construction process. The design of most impoundments is controlled by the type of waste to be impounded and the type of facility which the impoundment will serve. Table 5-2 provides a checklist of important data the designer must assemble and evaluate before beginning to design a waste disposal facility at a specific site.

5.2 Disposal Facilities with Liners of Soils and Clays

Unlike other engineering works in which manufactured structural materials with code-prescribed properties are used, in the case of soil-liner construction, there is often an economical need to use the existing in-place soil material. This is the situation if a prior analysis has proven the soil material to be an acceptable material for being "improved" as a liner.

5.2.1 General Discussion

Because of soil variability and the scale of the operation, in the case of designing and constructing a soil liner, a relatively larger flexibility has to be provided by the designer in the specifications required. These specifications have to be both essential and operational; they have to be stated in terms of performance required from the soil liner and also in terms of methods of achieving the required performance.

A very important feature of the construction operation of a soil liner is the inspection of the adequacy of the work performed. This is done by visual observation and testing. Although a large amount of experience has been accumulated in constructing similar structures, e.g. dams, canals, embankments, etc. relatively little is known about the construction of soil liners of large areas; accordingly, the quality control function should be given a high priority. The inspection work should be performed during construction and the amount of effective inspecting work will depend on the ability of the quality control team, its cooperation with the construction group and the capacity of the contractor to "learn while doing" and improve his performance. To assist the inspection operation, a field laboratory should exist, or better, access to a qualified laboratory should be available. The effort should be such that, at any time during the construction of the soil liner, a clear qualitative assessment can be made at to whether the work performed complies with the specification.

Heterogeneity of soil is the rule rather than the exception; it is "the nature of the beast". The design specifications, based on all pertinent information, must provide the contractor who performs the site improvement (the construction of the soil liner) with all needed information. The specifications have to state clearly the working procedures for every soil type or unit so that the end result will be a uniform soil liner.

The working procedures indicated in the design specifications for a particular soil unit normally would be easy to observe if the soil cover were to have a uniform moisture content and density characterization in the undisturbed state; oftentimes, though, there is a soil intraunit heterogeneity which can escape observation during the the reconnaissance investigation. The

TABLE 5-2. RELEVANT BACKGROUND INFORMATION HELPFUL DURING SITE SELECTION PROCESS

USER INFORMATION

Owner's name
Owner's location and telephone number
Design engineer
Operator's name
Site and facility location

METEOROLOGICAL DATA

Temperature - high, average, low
Wind direction, velocity
Precipitation - snow, hail

PROCESS DATA

Waste description
Relevant waste characteristics
pH
Temperature
Composition of waste
% Solids
Quantity
Unusual variations, e.g. loading, chemicals, temperature

FACILITY NEEDS AND CHARACTERISTICS

Capacity
Dimensions
Longevity
Harvesting or reclamation program(s)
Aeration program - equipment and methods
Waste flow variation and discharge velocity
Inlet system
Outlet system
Venting systems
Lining penetrations
Regulatory agencies
    Names
    Addresses
Monitoring requirements

slight adjustment of the instructions to the newly discovered state of the soil depends on the competence of the working group.

The construction of a soil liner is the field operation in which in-place or imported soil material is compacted and remolded such that the seepage through it is restricted. The most important purpose in producing such a blanket is to impede waste-effluent flow. Since this is done by soil densification, the contractor and the quality control have to provide evidence that:

a. The design density is achieved.

b. At these density specifications, the soil has indeed the designed flow properties.

The highest priority of the quality control has to be in checking item (a); the quality control has to cooperate fully with the designing group in assisting the investigations in item (b).

The operational specifications refer to the following:

a. The depth of the soil liner.

b. The required moisture-content of the undisturbed soil to produce the desired density.

c. The depth of the unit-layer to be compacted at one time.

d. The number of passes of the compacting implement over one unit-layer.

e. The weight of the compacting implement.

f. The type of compacting implement.

g. Possibly the trade-name of the compacting implement.

All these operational specifications have to be rigorously observed by the constructing team.

5.2.2 Testing of Soil for Selection and Design of Liner

The principal requirements that a soil must meet for use as a liner for waste disposal facilities are:

a. Low permeability to water and waste fluids.

b. Little or no interaction with the wastes which might increase permeability.

c. Absorptive capacity for pollutant species.

d. Strength initially and after contact with waste fluids to maintain slope stability.

In addition to the above principal soil requirements, the history of the candidate soil must be investigated to determine its prior use or exposure to hazardous, toxic or other undesirable elements which might affect the function of the waste impoundment facility. For example, monitoring the performance of a liner constructed with soil contaminated with a toxic substance would very likely show that substance below the liner at some point in time, even though the liner was functioning properly, and that particular substance had never been placed in the impoundment facility. This study of the subgrade soil may require chemical analysis of the soil and the pore water therein.

This subsection is concerned with the laboratory testing of the candidate soils for possible use as a liner at a particular waste disposal facility. This testing should be incorporated in the soil selection process and in designing of the liner to insure the adequacy of the soil selected and to form the basis of the design.

5.2.2.1 Atterberg Limits

The determination of liquid and plastic limits is essential for both classification purposes and behavioral assessments (Section 3.2.3.1). The liquid limit of soils should be determined by ASTM D423 and the plastic limit and plasticity index by ASTM D424 for classification purposes.

If reasons exist to suspect that the soil is sensitive to the chemical composition of the waste fluid, one may wish to perform a compaction study. Two variables should be considered: (1) the seasoning period, i.e. the length of time in which the soil is cured with water and, (2) the chemical composition of the fluid used. If, in comparison with distilled water, a 0.01 N $CaSO_4$ solution produces drastic changes in plastic properties, a waste leachate should be obtained and used in determining the limits. The generated results should constitute the starting point for the investigation of flow, volume change, and strength characteristics of soils.

5.2.2.2 Determination of Moisture-density Relationships

In different sections of the manual, e.g. Sections 3.2.2, 3.2.3, and 4.2, it is emphasized that soil compaction or densification in the field should be performed in order to obtain a soil blanket with low permeability. In the case of soils with sensitive structures, the low permeability is achieved not as much through densification as by a structural improvement of the soil. This aspect of the problem raises serious doubts about the terms "densification" or "compaction". Indeed, since the in-place soil is the material which is improved in a soil liner, the improvement is done by "remolding and recompacting" the soil.

To reproduce this procedure in laboratory condition, advantage has been taken of available information regarding the effect of compactive effort and of different compaction methods on soil structure and flow properties. Accordingly, a minimal test program should comprise both static and kneading compaction procedures. The research should be concentrated on the "wet-of-optimum" which has greater flow-sensitivity implications for the soil. However, the degree of sensitivity can be ascertained only when permeability tests are conducted on soil samples which have been compacted at known combination of density and moisture content. Thus, it becomes clear that the two aspects (compaction and permeability) are related and compaction efficiency should be investigated as a comprehensive test program.

To generate a moisture-density relationship, we recommend ASTM D698 and ASTM D1561. Additional information can be obtained by comparing the results obtained by ASTM D1557 with those obtained by the low-compacting effort method, ASTM D698. When using the kneading compaction method, ASTM D1561, it is important to vary the thickness of the compacted layer and/or the amount of compactive energy per layer.

5.2.2.3 Permeability to Water

A clay soil's permeability (K) is a numerical value representing its ability to transmit fluid. From Darcy's law for liquid flux through a porous medium, it can be seen that a soil K value is independent of the volume of soil, the volume of fluid passing, and the hydraulic gradient moving the water:

$$J = \frac{Q}{A} = K\Delta H$$

where:

J = flux of a fluid ($cm^3 cm^{-2} s^{-1}$)

Q = flow ($cm^3\ s^{-1}$)

K = permeability coefficient ($cm\ s^{-1}$)

ΔH = hydraulic gradient

A = cross-sectional area of flow (cm^2)

and since:

$$Q = \frac{V}{t}$$

where:

V = volume of fluid (cm^3)

t = time (s)

therefore:

$$K = \frac{V}{At\Delta H}\ .$$

Darcy's law assumes direct proportionality between the hydraulic gradient (ΔH) and the flow rate (Q) where flow is laminar. Accordingly, any change in the permeability coefficient (K) will represent a change in the porous media.

For comparison of a clay's permeability to different fluids, the fluid's viscosity and density must be incorporated into Darcy's law along with the gravitational constant. So adjusted, the permeability coefficient is changed to the intrinsic permeability coefficient (IPC):

$$K' = K \frac{n'}{G}$$

where:

K' = IPC expressed in the c.g.s. system as cm^2

K = permeability ($cm\ s^{-1}$)

n' = kinematic viscosity ($cm^2\ s^{-1}$)

with

$$n' = \frac{n}{\rho}$$

n = viscosity ($g\ cm^{-1}\ s^{-1}$)

ρ = density ($g\ cm^{-3}$)

G = gravitational constant, 981 $cm\ s^{-2}$ at 45° latitude.

Viscosity normalizes a fluid's resistance to flow due to its cohesiveness, while the fluid's density values normalizes the effect of gravity on its flow. Use of IPC values permits the addition of K' values where there is more than one fluid flowing through a soil.

A representative sample of the spectrum of organic fluids being placed in waste impoundments is being investigated to determine their effects on the permeability of clay liners. Central to these tests has been the development of a constant pressure permeameter suitable for permeability measurements of compacted clay liners subjected to organic chemicals. The test apparatus and methods for the permeameter are given in Appendix III-D.

Several factors not incorporated into these laboratory tests enter into a clay's overall permeability. Sherard et al. (1963) listed the primary factors determining "effective overall permeability" of a layer as: continuity, regularity, thickness, and characteristics of interbedded layers or lenses. A laboratory determination of permeability cannot take into account this type of variability in a clay liner. It attempts to characterize only a homogenized sample of the clay soil. Nevertheless at this point we must rely on laboratory tests.

5.2.2.4 Permeability to Waste Fluids

The previous subsection presented the permeability of water through a clay or soil medium. This section is concerned with the permeability of soils to waste fluids. This topic and related topics have been discussed in detail in Subsections 2.2.5, 3.2.2, and 3.2.3, as well as Sections 4.2 and 4.3. These sections stated that the interaction of clays and soils with various waste fluids can be adverse, resulting in the loss of the structural and chemical integrity of the liner. The range of waste fluids that have been tested is by no means extensive or exhaustive. Much research work remains to be done related to individual wastes not yet tested. Before finalization of design and initiation of construction, compatibility testing of the expected wastes to be contained with the proposed liner types should be conducted. As a minimum the modified Atterberg Limits test plus some pilot or laboratory scale permeability testing should be conducted. Presented in Appendix III is an experimental permeameter which can be used for accelerated testing.

5.2.2.5 Determination of Soil Strength Characteristics

It is well known that in laboratory testing of a soil for strength characteristics, the relevant failure mechanism of the soil in the field should be well understood. Of particular significance are pore-water pressure changes and their relation to soil strength. If field volume changes are prevented, pore-water pressures can develop in the soil. The simple situation in which the soil accepts water under a certain confinement and then deforms in shear without change in volume, can be duplicated in the laboratory in a consolidated-undrained triaxial compression test (CU-test). For this purpose, ASTM D 2850 should be used with the provision that volume changes are permitted while the sample is under T_3loading (chamber pressure).

Despite its tremendous advantages, triaxial testing has its limitations. One of the important drawbacks is that in the apparatus the sample can reach only a limited strain, sometimes considerably below the values of strains required in slope stability analysis; this is particularly true with cohesive soils. On the other hand, it may be more meaningful to perform an extension rather than a compression test since this condition seems to reproduce slope failure better.

Apart from the triaxial technique, either a direct shear or a vane shear apparatus can be used to determine soil strength characteristics. The most important fact to be remembered is that the possible failure mechanism must be reproducible in the laboratory.

The strength properties of clayey soils are important not only with regard to slope stability, but also with regard to the task of compacting the soil at a particular desired density. It has been suggested that, in the case of plastic soils, if the moisture-density relation is such that a California Bearing Ratio (CBR) value lower than five is obtained, the roller will do a poor compacting job since the soil will tend to "ball up" and the roller may not "walk out" properly (Burmister, 1964).

In the design of a sloped soil liner, the first approach should be to compact the soil using the parameters which are considered to generate the least permeable soil, i.e. without consideration of strength properties. If, by using this procedure, a critically weak soil is generated (safety factor less than 1.2), then ways to improve strength properties should be investigated by testing; the main task should be to ascertain the most economical way of improving the strength of the soil liner associated with the least detriment to soil permeability characteristics.

The exact conditions which have to be observed during the field compaction to obtain the highest safety factor cannot be explicitly stated; Seed et al. (1960) wrote: "Since the influence of these factors are often conflicting - for example a flocculated structure promotes high strength at low strains but it also promotes high expansion characteristics - a variety of patterns relating undrained strength after soaking in initial compaction can be obtained for various types of soil."

The observations described in this section with regard to the effect of varying compaction conditions upon strength should be considered only as indicative of what may happen with any particular soil. In this discussion, the emphasis is deliberately placed on the effect of soil structure on strength; this is not to say that chances of encountering a structure-sensitive soil are very large. Probably, the reverse is true. The over-estimation of structural effects in our discussion is made because:

a. Structural aspects are relatively more important in the group of cohesive soils with a relatively high clay content.

b. In basic geotechnical literature, relatively little information is found on the subject.

When the topography of the waste disposal site is flat, soil strength characteristics are of little concern. Environmentally, a disposal site should be placed as far away as possible from highly populated areas, which are mostly flat areas. The disposal sites may consequently be pushed into hilly, dissected topography regions. A hilly region has its advantages in that placing the waste in a ravine may involve generally less earthwork and results in a higher efficiency of waste storage per unit disposal area. In many situations, the waste disposal site floor will slope and so will the soil liner. For this situation, an investigation of stress-strain and strength properties of the soil should be conducted. The difficulties associated with the analysis of slope stability are not associated with the usual difficulty in properly determining the cohesional and functional characteristics of the soil, but rather with a proper estimation of the characteristic hydrology of the site under operating conditions; in other words, changes in the hydrology have to be estimated, average and "worst" patterns have to be identified, and all information integrated into a factor of safety using pertinent methods of analysis.

Since one of the basic requirements with regard to a soil to be used as a liner is its relatively high clay content, and since such soils are called "cohesive" because of the presence of cohesion when undisturbed, it should be mentioned that most of the normally consolidated remolded soils lack such a cohesion (Seed et al., 1960). This observation was made with the consideration that any compaction operation is, to a certain degree, a remolding operation.

As Mitchell (1969) stated, "Perhaps the single most important reason for soil compaction is to increase the soil strength". It has been shown that CBR strength of a silty clay is directly related to the density achieved over a wide range of moisture contents. As has been shown (Mitchell, 1969), at water contents over the optimum, the CBR strength was also affected by the water content during compaction.

The strong dependence of the "as-compacted" CBR strength on density at moisture contents below the optimum moisture is evidence of the minimal structural effect; in this range of moisture content densification because of a higher compactive effort is not associated with a considerable deflocculation of the soil structure. The strength is a strongly correlated function of density. The opposite happens in the wet-side-of-optimum range where it is observed that irrespective of the magnitude of the compactive effort, the strength is the same at a particular moisture content (Burmister, 1964). Slightly higher densities obtained with greater compactive efforts and an eventual increase in strength effect are offset by a more deflocculated (weaker) structure.

The method of compaction has also a very large effect on soil strength. Its effect is manifested mostly on the wet-side-of optimum (Seed and Chan, 1959; Seed et al., 1960). Whether a static or a kneading compaction procedure is used on the dry-side-of optimum, the characteristic structure of the soil will be the flocculated and, at the same moisture content and density, the strength will be unaffected by the method of compaction. In the high range of moisture content, the kneading compaction is much more efficient in deflocculating the structure and, at the same density and moisture content, the soil is considerably weaker than the soil compacted statically. Seed et al. (1960) performed unconsolidated-undrained (UU) strength tests on a compacted silty clay soil and found that the statically compacted samples were four times as strong as those compacted by kneading. As Seed et al. made clear, only the general trends of the observed behavior can be considered as being valid; strength properties of soils can vary appreciably with regard to the compactive effort and the method of compaction.

The observation revealed by the work performed at the University of California, Berkeley, that the strength of the statically compacted soil is greater than the strength of the soil compacted in a kneading device refers to values of shear stresses recorded at relatively small strains (5%). When values of shear stresses corresponding to larger strains (20%) were considered, no differences were found. The explanation advanced was that the prolonged shear generated, in a statically compacted sample, a structure similar to the one characteristic for the sample prepared by the kneading compaction procedure, i.e. a dispersed one, which raises an important practical problem: in assessing the value of the shear stress for a particular design purpose, consideration has to be given to the range of meaningful strains.

Since the problem is one of slope stability, a safe procedure would be to consider the "ultimate" value of strength (Lambe) or the "residual" one (Skempton), which means "shear stresses at large strains".

It is known that, at the same void ratio, the strength of a flocculated soil is larger than the strength of a dispersed one (Mitchell, 1956), which reiterates the fact that, in the case of many clayey soils, the soil structure is of paramount importance. Often, the effect is so large that, if samples of the same soil subjected to different histories are brought to the same density and moisture content via soaking and consolidation or swelling, the stress-strain and strength properties will be still different because of the difference in the initially established structure (Mitchell, 1964). This structural difference will generate different patterns of pore-water pressure development with the result that, if the strength of these structurally different soils were to be assessed in terms of effective stresses, no difference in strength would be found between the two samples (Seed and Chan, 1959).

Pore-water pressure characteristics of a soil during shear are a reflection of clay structure which depends on the chemical and mineralogical characteristics of the clay. It has been proven that even a partial replacement of an exchangeable cation by another can substantially alter the strength of clays (Moum and Rosenquist, 1961). Since the waste effluent differs in chemical composition from the pore-water solution, cation exchange reaction can be anticipated which can have a substantial effect on strength and permeability properties of the soil.

While the strength of an "as-compacted" soil can be determined relatively easily, the strength of the in-place soil liner is harder to determine. Saturation, consolidation, or swell are some of the important changes which can operate in the field with important repercussions on stress-strain and strength properties (Seed et al., 1960). The relatively simplified situation in which the soil soaks under a certain confining pressure and then is loaded to cause deformation at constant volume is simulated in the laboratory by a consolidated undrained (CU) test; this is the usual procedure for assessing soil strength for pavement and earth dam designs. In this situation, the strength will be dependent on structural characteristics and void ratio since both determine pore-water pressure characteristics during shear. Samples of a silty clay soil, prepared by kneading compaction at different densities and moisture contents, if soaked with no change of volume, will be stronger with lower compacting moisture content if the stress at 5% strain is considered; at larger strains (20%), the strength is unaffected by the moisture content during compaction (Seed et al., 1960).

Regarding the stress-strain relationship and the way it relates to composition during compaction (density and moisture content), for structure-sensitive soils, the more flocculated the structure, the larger the shear-modulus, the stiffer the soil (Seed and Chan, 1959). In testing a silty clay soil in consolidated undrained compression (σ_3 = 2.0 kg cm^{-2}), it was shown that the lower the moisture content during compaction (the more flocculated the structure), the larger the deviator stress at any particular strain. Simultaneously, the pore-water pressure was higher with larger compaction moisture content so that the effective principal stress ratio or the effective obliquity index (σ'_1/σ'_3) was practically the same over a large range of moisture contents during compaction. This again emphasizes the functional relationship between chemical and mineralogical characteristics-structure-pore-water pressure strength (Mitchell, 1964, p. 89).

5.2.3 Designing Soil and Clay Liners

As a hydraulic structure, the soil liner shall be designed with the main purpose of obtaining a blanket which will considerably impede the downward movement of the waste liquid into the underlying, undisturbed soil. Soil strength considerations will not be looked upon in this section because of their secondary importance. If, for particular areas of the waste-disposal site soil strength characteristics are relevant (for instance, in conjunction with slope stability), the designer will recommend compaction procedures which will yield the required strength without detrimentally affecting the impermeability of the site.

Another facet of the design process for a soil and clay liners is the provision for keeping adequate construction records and documentation as well as retention of representative samples of field molded and compacted samples of liners and subgrade. The above records and samples will allow for timely and efficient verification of the construction and provide sufficient baseline data to evaluate ongoing performance.

The temporary immobilization of some contaminants along the depth of the soil liner is likewise not considered in this section, being probably negligible compared to the attenuation in the underlying soil often with a greater depth than the soil liner. Disregarding the attenuation capacity of the soil liner will produce an error on the safe side.

The starting point of the analysis for design should constitute the limiting seepage, the permissible flux q_p, between the soil liner and the underlying soil. This level of tolerable flux will be obtained as a result of a careful consideration of the following factors:

a. Waste-disposal site characteristics

  - Size
  - Shape and the angle between the long side of the waste disposal site and the direction of groundwater flow.

b. Waste-effluent characteristics

  - Number of pollutants at a dangerously high concentration
  - The concentration (c) of the pollutant for which there is the highest ratio c/d.w.s. (d.w.s. = drinking water standard)

c. The attentuation capacity of the underlying soil and its capacity to render groundwater contamination less probable.

d. Groundwater characteristics

   - Depth

   - Flow rate.

e. The sink-source distance, i.e. the distance between the contamination point (the waste-disposal site) and the usage point (the well depleting the aquifer).

Once the q_p value (the seepage between the soil-liner and the underlying soil) is obtained its value should be incorporated into the analysis to generate the soil permeability K for the known geometry characteristics and material properties of the system. A discussion of such an analysis is provided in Appendix VII.

As it has been indicated in previous sections on testing procedures, three main soil characteristics have to be investigated:

a. Soil compactibility

b. Soil flow properties

c. Soil chemical sensitivity.

Soil compactibility is determined by performing the Proctor compaction test. The results, the optimum moisture and particularly the maximum density, have to be judged by the designing engineer using background information on texturally similar soils.

Soil flow properties shall be determined on samples prepared using one of the indicated ASTM procedures. The fluid to be used, at this stage, is either tap water or 0.01.N $CaSO_4$ solution. The results of this test, coupled with the Proctor compaction data, will reveal the ranges of soil moisture content during compaction and soil densities where soil permeability drops below the required soil permeability corresponding to the permissible flux q_p. Comparing the two sets of data (soil compaction and soil permeability), the designer will be faced with the following situations:

a. There is a broad range of moisture content (w) and of soil bulk density (p) where the permeability (K) is less than the permissible permeability (K_p). Moreover, the two ranges practically overlap. This is expressed in Figure 5-4 by a unique relationship between p and K.

   This situation is the safest possible and the design engineer should not have any problems in optimizing the moistureof the soil during compaction and the corresponding density. If, in the tentative

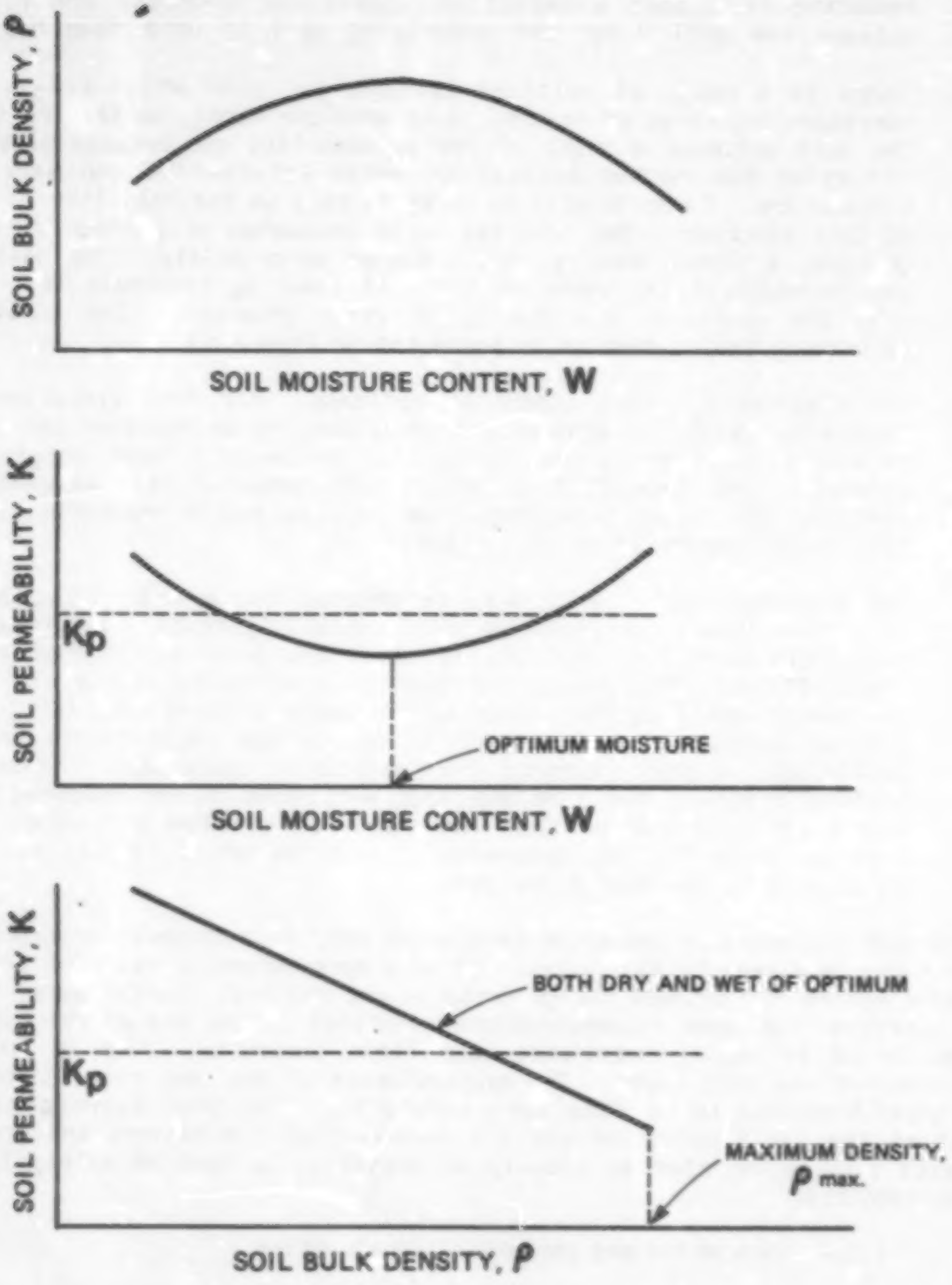


Figure 5-4. Schematic representation of the relationships w-ρ, w-K and ρ-K, for an idealized soil with no particle orientation when compacted at high moisture content. (Case 1).

calculations, the depth of the soil liner D_e was on the high side (around 5 feet), the findings of the two tests reveal a way of reducing it. Such a reduction should not increase the flux q between the soil liner and underlying soil to more than 0.8 q_p.

b. There is a range of moisture content (w) over which $K<K_p$. The corresponding range of density is in absolute terms, on the low side. The soil achieved a state of low permeability not because of densification but rather because of shear deformation and particle orientation. Since it will be risky to rely on the stability in time of this structure, the soil has to be compacted at a lower moisture content, a higher density, and a higher permeability. The designer has to readjust the depth of the soil liner D_e (increase it), such that the condition $q = 0.8\ q_p$ is still observed. The condition describing this situation is presented in Figure 5-5.

c. The required K_p value cannot be obtained. For this situation the only alternative, if economically feasible, is to increase the depth of the soil liner D_e and design for a larger K than originally planned. The import of a better soil material or fundamentally changing the lining technology (admixes, polymeric membranes, etc.) have to be considered at this stage.

The Atterberg limits which were recommended for assessing the merits of a soil liner, represent basic compatibility tests. Performed in parallel, with 0.01 N $CaSO_4$ solution and with a representative waste effluent, they reveal the chemical sensitivity of the soil. If the limits are markedly altered by the waste effluent compared to the calcium sulphate solution, and if the design requirements can be barely met, a short research program becomes compulsory. In such a testing program, the remolded specimens have to be prepared with waste effluent rather than tap water or calcium sulphate solution and their K values determined. This new set of results has then to be used in the design analysis.

The preceeding discussion has to be considered only as a recommended procedure in using the test results for design. Often a more extensive research program is needed before the optimum design criteria are reached. Furthermore, it is to be expected that some recommendations generated at the end of the testing program cannot be easily translated into field compaction criteria for the preparation of the soil liner. The extrapolation of the test results for the field condition has to be done very carefully. The best approach is to understand the field condition and the construction limitations and perform the tests paralleling them as closely as possible, so that no extrapolation will be required.

5.2.4 Excavation and Embankment Construction

5.2.4.1 Excavation and Sidewall

After planning and design stages are completed, construction activities commence. In most instances, the "earthwork" is accomplished by a general

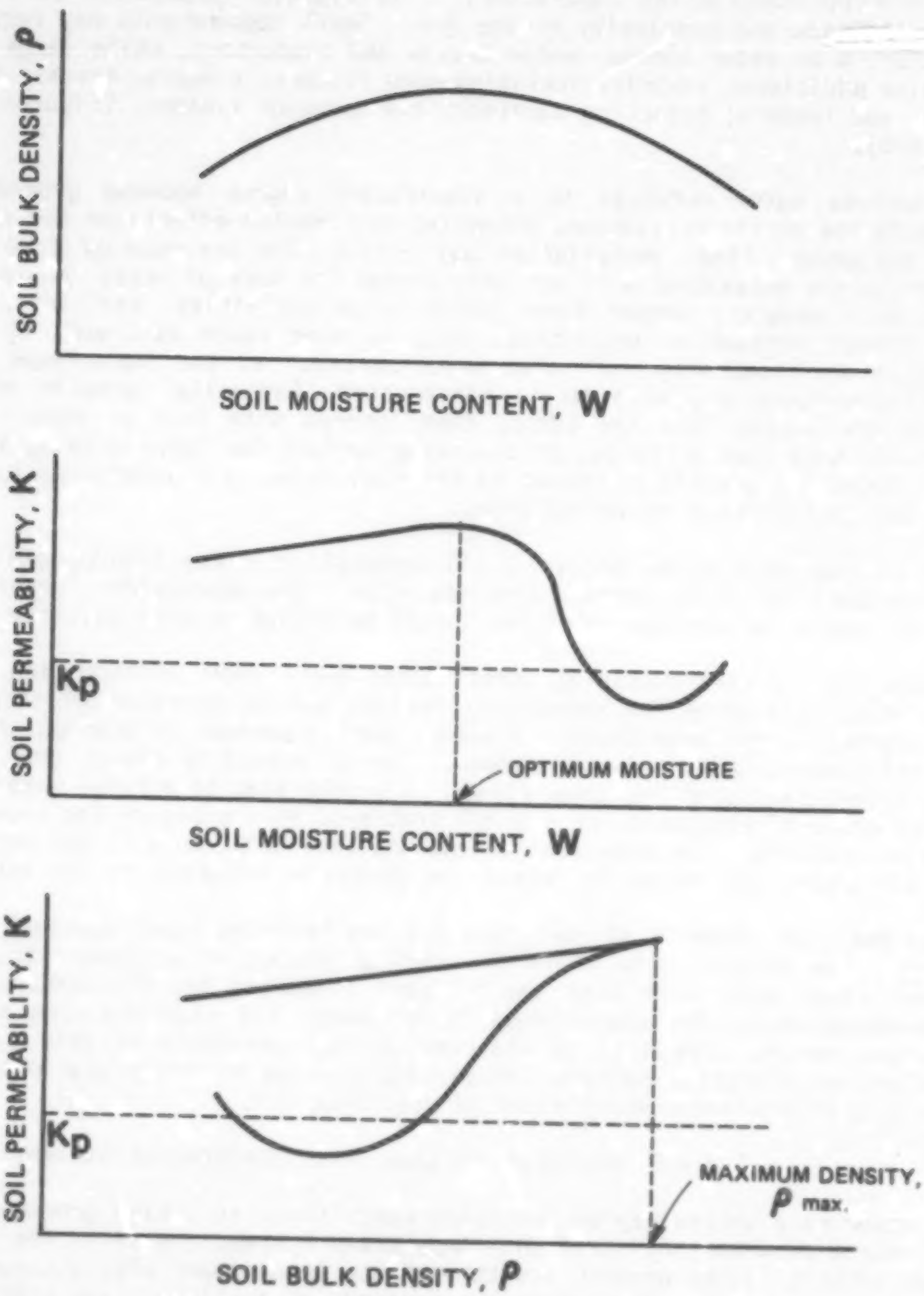


Figure 5-5. Schematic representation of the relationships w-ρ, w-K and ρ -K, for an idealized soil with no particle orientation when compacted at high moisture content. (Case 2).

engineering/construction contractor. The types of equipment utilized vary with the size and complexity of the job. Small impoundments may require only tractors with dozer blades, water trucks and compactors, while large jobs may require additional vehicles including side loaders, graders, trucks, backhoes, front end loaders, trenching machines, and conveyor systems. (Figures 5-6, 5-7 and 5-8).

If surface water develops to a significant degree because groundwater is encountered during excavation, potential detrimental effects on the success of the subsequent liner installation may evolve. The presence of free standing water in the excavation will not only hinder the work of heavy equipment, but also will severely hamper liner installation activities. Similarly, rainfall can hinder excavation activities, and, in some cases halt work by creating adverse trafficability. If free water persists at the impoundment base, an artificial base may have to be constructed. Generally, gravels of various sizes are packed into the earth, then covered with sand or other available material such that a stable, firm working surface for later grading is achieved. Costs are greatly increased by the need to build a water-free surface for a liner installation in wetted areas.

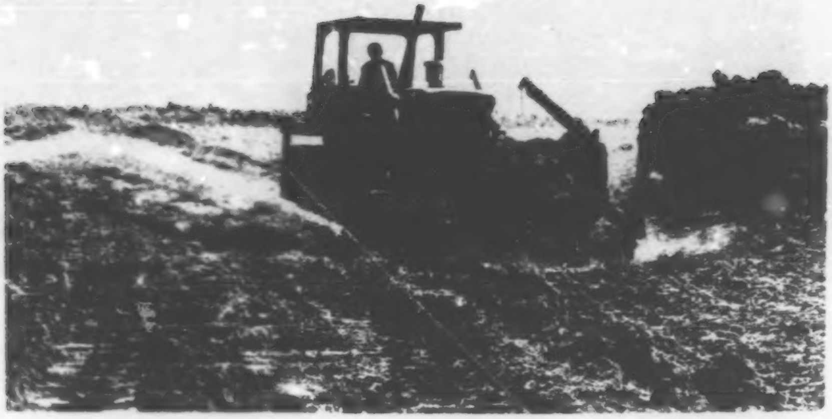
During the excavation process, all vegetation (tree trunks and roots in particular) should be removed from the site. Any depressions resulting from stump removal or similar condition should be filled in with suitable backfill.

Slopes will be constructed by normal techniques. Most construction equipment including self-propelled compacting rollers can be operated on slopes up to 3:1 during normal conditions. However, during periods of precipitation, even on 3:1 slopes, additional arrangements may be needed to ensure that equipment can travel safely up and down slope. A simple link to a large dozer, another heavy piece of equipment, or a winch stationed at the top of the sidewall/berm can be utilized. The equipment at the top then helps to pull the working unit up the slope, and helps to retard its downslope progress on the return trip.

When the side slope is steeper than 2:1 the "helping hand" approach is mandatory. One method is to chain two similar pieces of equipment together for cross slope work, such that the "helper" traverses the flattened top of the embankment while its chainlinked "twin" works the slanting side slope. Of course, extreme care must be observed during operations of this type. Road graders or vibrating rollers linked side-by-side by chain are an example of the type of equipment which might be used like this.

5.2.4.2 Drainage and Leak Detection/Control Systems

An underdrain system may be necessary where there is a high groundwater table or source of water infiltration. Underdrain systems may serve the purpose of transmitting fluids beneath and through the impoundment site without interaction with any contaminants from the impoundment facility. Kays (1977) identifies the following five parts in an underdrain system: (1) interceptor, (2) collector, (3) filter, (4) conveyor, and (5) disposal mechanism (See also Cedergren, 1967.)



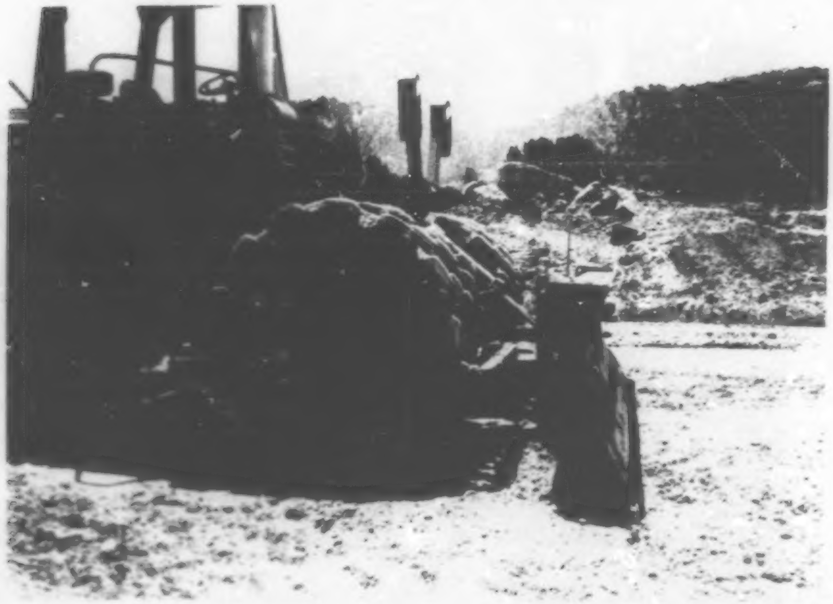


Figure 5-6. Typical earthwork equipment used during impoundment construction, dozer with blade top) and dozer with compactor and blade (bottom).

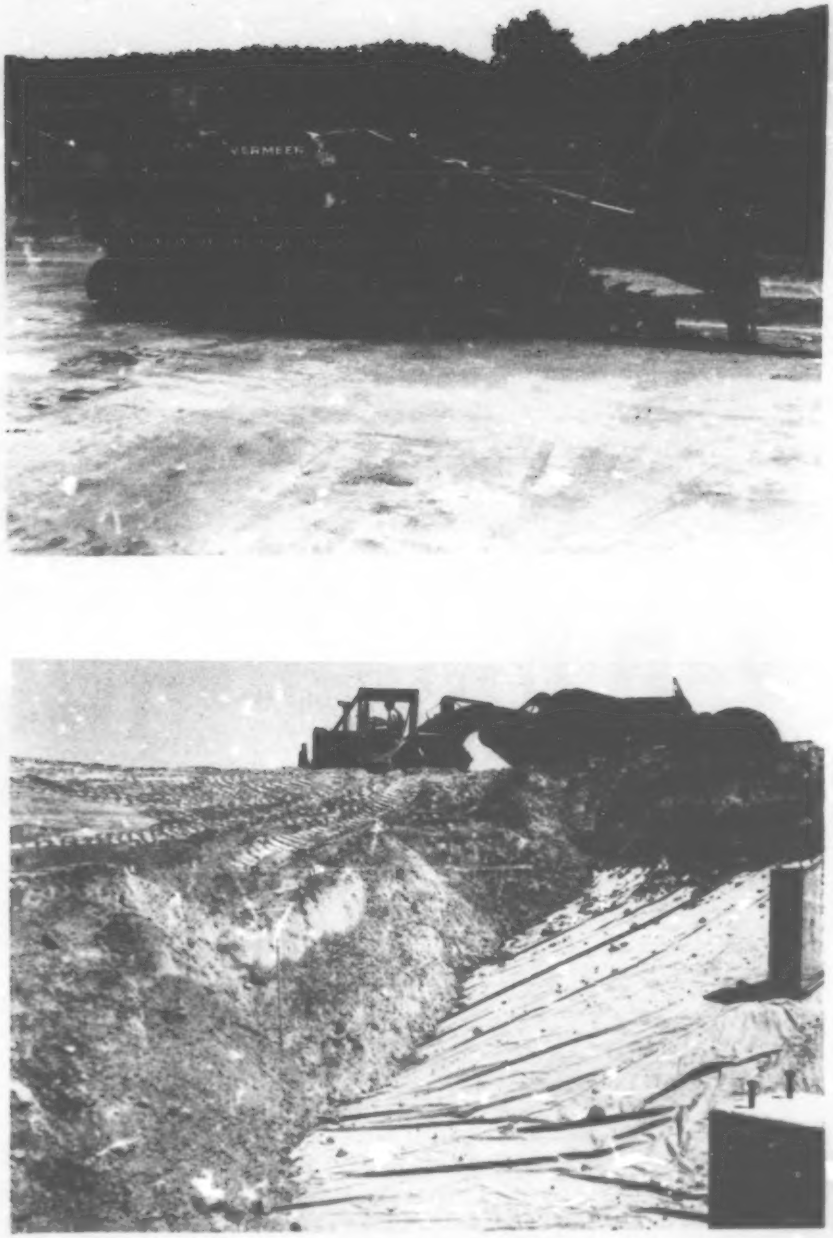


Figure 5-7. Trenching machine for anchor trenches (top). Dozer and earth mover for berm construction (bottom).

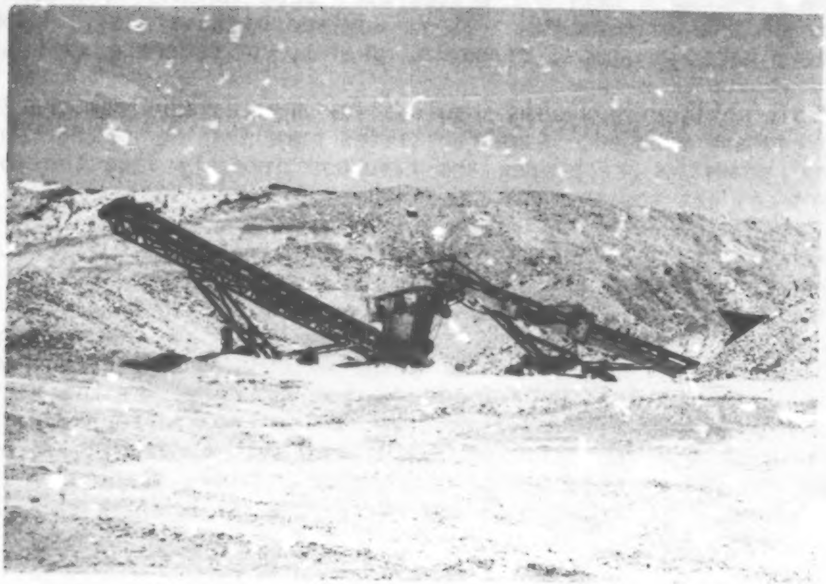


Figure 5-8. Conveyer system used during impoundment construction.

The interceptor receives any liquids resulting from leakage or natural drainage. Interceptors should underlie the entire facility, including the sidewalls if they are to be effective. Usually, the interceptor is composed of the following three parts: (1) an impervious base layer, (2) an overlying permeable lattice layer, composed of gravel, open graded asphalt or some other suitable material, and (3) a covering layer to protect the overlying liner from penetration by the permeable lattice materials; fabric materials (like filter blankets), graded earth, coarse sand, and others are in use.

The function of the interceptor is to convey seeping fluids to the collector. The collectors are generally located in blankets or trenches in the bottom of the facility with the number of feeding collectors being dependent on the size of the impoundment and the collector's basic design. Underdrain tile and perforated pipe have been used for the collector system.

Filters are required where there is a danger of the lining material fines (clay lining) working into the interceptor material. Filters can be constructed in the field of graded permeable soils, or may be one of the many commercial filter media now available. The purpose of the filter is to stop the migration of particles within the system. The movement of particles into the conveyance and collector can and will eventually inhibit the acceptable operation of the underdrain system. Any sign of turbidity in liquid issuing through the underdrain system could be a sign that the filtering system may be failing. According to Kays (1977), "The filter is an item often neglected in an underdrain complex. Its omission is responsible for triggering many malfunctions."

The underdrain monitoring system feeds into a closed pipe conveyance. The conveyance system must be sized to handle more than the expected optimal flows, as any backup within the system can cause serious repercussions (e.g. instability of the embankment). It is advised by Kays (1977) that the conveyances terminate in sumps, channels, drains, or concrete exit structures.

The underdrain monitoring system should allow any leakage from the impoundment to be detected and managed. Some facilities have pumping arrangements whereby leakage and underflow are pumped and returned directly into the impoundment, while others collect the seepage and dispose of it offiste.

A critical need for an adequate drainage system will exist if groundwater is present immediately below the impoundment. A well designed underdrain system will mnimize or eliminate (1) reverse hydrostatic pressure and (2) removal of soil from beneath the liner due to groundwater flow. Reverse hydrostatic pressure occurs when the groundwater level exceeds the operating water level in the impoundment. This could occur, for example, during normal level fluctuations in a drinking water reservoir. The groundwater reverse pressure can then push on the back side of the lining system, causing liner failure. Soil may be removed by groundwater flow below a liner, eventually causing the liner to rupture. If possible, sites where high groundwater exists should be avoided.

5.2.4.3 Monitoring Wells

Facilites which store toxic/hazardous wastes will be required to monitor the condition of ground and surface water adjacent to the impoundment. Frequently, observation wells are drilled using normal techniques, standpipes inserted, and samples are taken and analyzed periodically. Most monitoring wells are open pipes into which a water sampler can be lowered.

5.2.4.4 Field Compaction of Soil for Construction of Liner Waste Disposal Facilities

The compaction of soil is an essential step in the construction of all types of liners, whether they be soils for a clayey soil liner or for a subgrade on which admix, flexible membrane, or spray-on liners will be installed. Since the soil liner must have low permeability, emphasis in the compaction of soil for use as a liner is placed on achieving as low permeability as feasible. The requirement for strength is secondary, but it is needed for the embankments and dikes. For the subgrade, compaction of soil is needed to improve structural strength, uniformity of the subgrade, and smoothness. The subgrade sidewall particularly needs improved strength for stability. In this subsection, field compaction of the soil, the equipment, and the field tests required in the construction of lined waste disposal sites are described.

The applicability and requirements for the various pieces of compaction equipment that can be used to achieve desired compaction is presented in Table 5-3 taken from Coates and Yu (1977), pp. 90 - 91. The adequacy, use and efficiency of each piece of equipment varies with numerous factors including the following: (a) type, (b) weight and transmitted energy, (c) thickness of layers, (d) placement water content, and (e) material to be compacted.

Table 5-3. COMPACTION EQUIPMENT AND METHODS[a]

Equipment type	Applicability	Requirements for compaction of 95 to 100 per cent Standard Proctor, maximum density					Possible variations in equipment
		Compacted lift thickness, in. (cm)	Passes or coverages	Dimensions and weight of equipment			
Sheepsfoot rollers	For fine-grained soils or dirty coarse-grained soils with more than 20% passing No. 200 mesh; not suitable for clean coarse-grained soils; particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important.	6 (15)	4-6 passes for fine-grained soil; 6-8 passes for coarse-grained soil	Soil type	Foot contact area, in.^{2} (cm^2)	Foot contact pressures, psi(MPa)	For earth dam, highway, and airfield work, drum of 60-in. dia. (152 cm), loaded to 1.5 - 3 tons per lineal ft (43.7 - 87.5 kN per lineal m) of drum generally is used; for smaller projects, 40-in. dia (101 cm) drum, loaded to 0.75 to 1.75 tons per lineal ft (21.9 - 43.7 kN per lineal m) of drum is used; foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass.
				Fine-grained soil PI > 30	5 - 12 (32 - 77)	250 - 500 (17 - 34)	
				Fine-grained soil PI < 30	7 - 14 (45 - 90)	200 - 400 (1.4 - 2.8)	
				Coarse-grained soil	10 - 14 (64 - 90)	150 - 250 (1.0 - 1.7)	
				Efficient compaction of wet soils requires less contact pressures than the same soils at lower moisture contents.			
Rubber tire rollers	For clean, coarse-grained soils with 4 - 8% passing No. 200 mesh.	10 (25)	3 - 5	Tire inflation pressures of 60 to 80 psi (0.41 - 0.55 MPa) for clean granular material or base course and subgrade compaction; wheel load 18,000 - 25,000 lb (80 - 111 kN); tire inflation pressures in excess of 65 psi (0.45 MPa) for fine-grained soils of high plasticity; for uniform clean sands or silty fine sands, use large size tires with pressure of 40 to 50 psi (0.28 - 0.34 MPa).			Wide variety of rubber tire compaction equipment is available; for cohesive soils, light-wheel loads such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased; for cohesionless soils, large-size tires are desirable to avoid shear and rutting.
	For fine-grained soils or well graded, dirty coarse-grained soils with more than 8% passing No. 200 mesh.	6 - 8 (15 - 20)	4 - 6				
Smooth wheel rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures.	8 - 12 (20 - 30)	4	Tandem type rollers for base course or subgrade compaction, 10 - 15 ton weight (89 - 133 kN), 300 - 500 lb per lineal in. (3.4 - 5.6 kN lineal cm) of width of real roller.			3-wheel rollers obtainable in wide range of sizes; 2-wheel tandem rollers are available in the range of 1 - 20 tons (8.9 - 178 kN) weight; 3-axle tandem rollers are generally used in the range of 10 to 20 tons (89 - 178 kN) weight; very heavy rollers are used for proof rolling of subgrade or base course.
	May be used for fine-grained soils other than in earth dams; not suitable for clean well-graded sands or silty uniform sands.	6 - 8 (15 - 20)	6	3-wheel roller for compaction of fine-grained soil; weights from 5 - 6 tons (40 - 53 kN) for materials of low plasticity to 10 tons (89 kN) for materials of high plasticity.			
Vibrating baseplate compactors	For coarse-grained soils with less than about 12% passing No. 200 Mesh; best suited for materials with 4 - 8% passing No. 200 mesh, placed thoroughly wet.	8 - 10 (20 - 25)	3	Single pads or plates should weigh no less than 200 lb (0.89 kN); may be used in tandem where working space is available; for clean coarse-grained soil, vibration frequency should be no less than 1,600 cycles per minute.			Vibrating pads or plates are available, hand-propelled or self-propelled, single or in gangs, with width of coverage from 1.5 - 15 ft (0.45 - 4.57 m); various types of vibrating-drum equipment should be considered for compaction in large areas.
Crawler tractor	Best suited for coarse-grained soils with less than 4 - 8% passing No. 200 mesh, placed thoroughly wet.	10 - 12 (25 - 30)	3 - 4	No smaller than D8 tractor with blade, 34,500 lb (153 kN) weight, for high compaction.			Tractor weight up to 60,000 lb.
Power tamper or rammer	For difficult access, trench backfill; suitable for all inorganic soils.	4-6 in (10 - 15 cm) for silt or clay; 6 in. (15 cm) for coarse-graded soils		30 lb (0.13 kN) minimum weight; considerable range is tolerable, depending on materials and conditions.			Weights up to 250 lb (1.11 kN); foot diameter 4 to 10 in. (1.57 - 3.93 cm).

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[a] Coates and Yu, 1977, pp. 90-91.

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The types of equipment in general use for gross compaction include sheepsfoot rollers, rubber tired rollers, smooth wheeled rollers, crawler tractors and tampers. Vibrating baseplate rollers, power tampers (or rammers) and manual tampers (or rammers) are used for fine finishing work both in the base and sidewalls. (See Figure 5-9). Power tampers and manual tampers are a necessity for backfill compaction of trenches or where penetrations of the base or sidewalls occur (e.g. around pipes, inflow/outflow/overflow structures and specialized supporting structures).

Compaction equipment can be selected based upon weight and transmitted energy requirements. For non-cohesive materials, compaction can be adequately achieved with track type crawler tractor and/or haulage units as light pressure and vibration is the most effective methodology. Frequently, complete drying and rewetting is necessary to destroy the bulking effect of surface tension created by soil moisture. Very firm compaction can be achieved on sands, gravels, and rock fill by the use of heavy vibratory wheeled compactors. Layers of cohesionless material up to 24 inches in thickness can be compacted with the vibratory rollers. Generally, stones in the cohesionless material should be no larger than two-thirds of the specified layer thickness (Coates and Yu, 1977).

Heavy sheepsfoot rollers, pneumatic rollers, and vibratory compactors are well suited for cohesive materials. The control of water content is essential in achievement of a high density with cohesive soils. When clay is the lining material and rubber-tired equipment is utilized for compaction, the surface of a given layer will be quite smooth after compaction. In certain instances where seepage might occur along this smooth plane, scarifying of the compacted layer to insure adhesion of the overlying layer will be necessary. Figure 5-10 shows two types of vehicles used to add water to soil prior to compaction.

5.2.5 Quality Control

Considering the extensive area of waste disposal sites (tens or hundreds of acres) and the need to generate a highly uniform soil blanket, the task of testing "representative" samples is important. It is essential to establish a statistically sound approach to sampling and testing. This will lead to the best return of information per dollar. In many situations, sampling from deliberately chosen spots where it is suspected that the earth work does not comply with the work requirements reveals an important characteristic of the work accomplished, that is, the relationship between the operationally stated requirements (which presumably were not fully observed) and the performance characteristics. In dealing with the problem of sampling and testing, the naturally existing heterogeneity has to be scaled. Failure to consider two basic groups of factors can result in the preparation of a soil liner of poor quality, e.g. the heterogeneity of the undisturbed soil cover and unjustified changes in working procedures for a particular soil unit.

5.2.6 Construction of Bentonite-Clay Liner

There are several methods available for the application of a bentonite clay lining. It can be used as a 1 or 2 inch thick membrane covered with 8 to 12

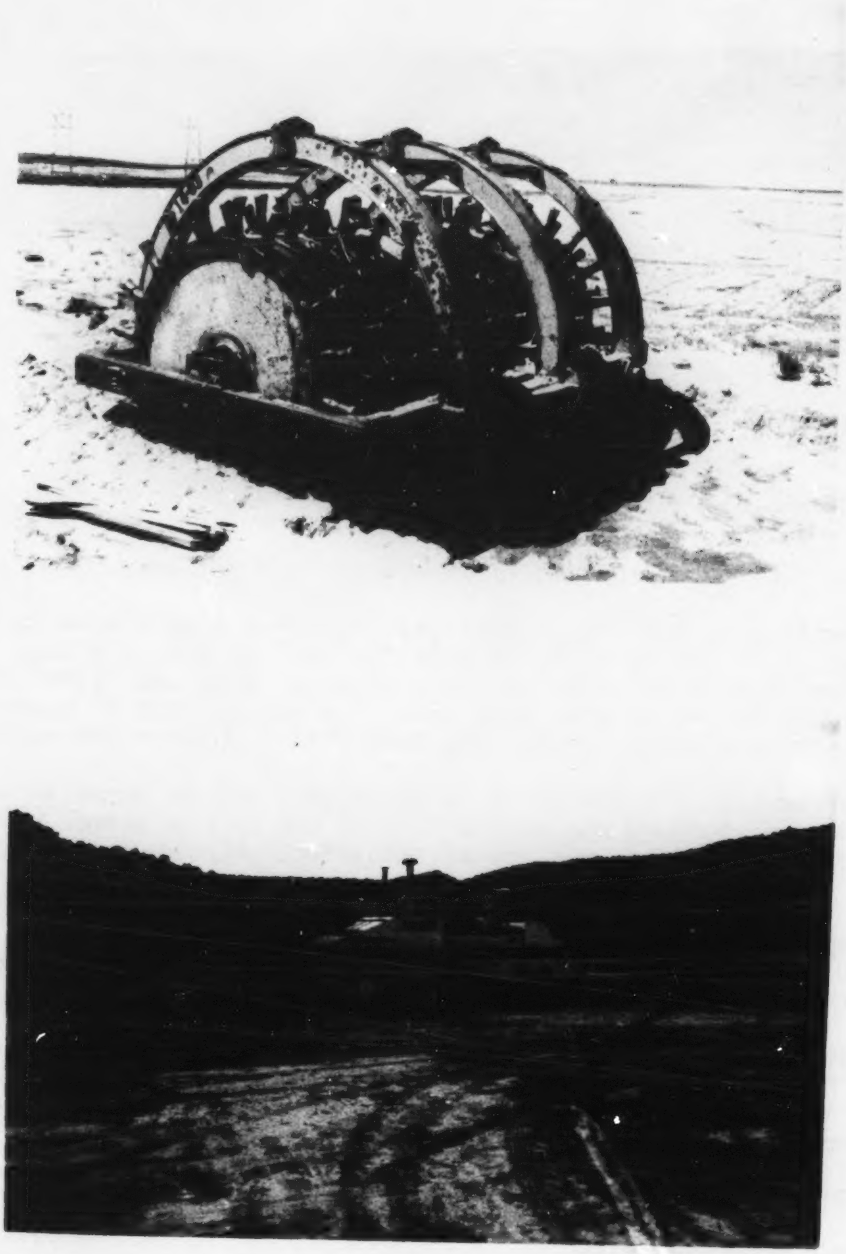


Figure 5-9 Typical compaction equipment.

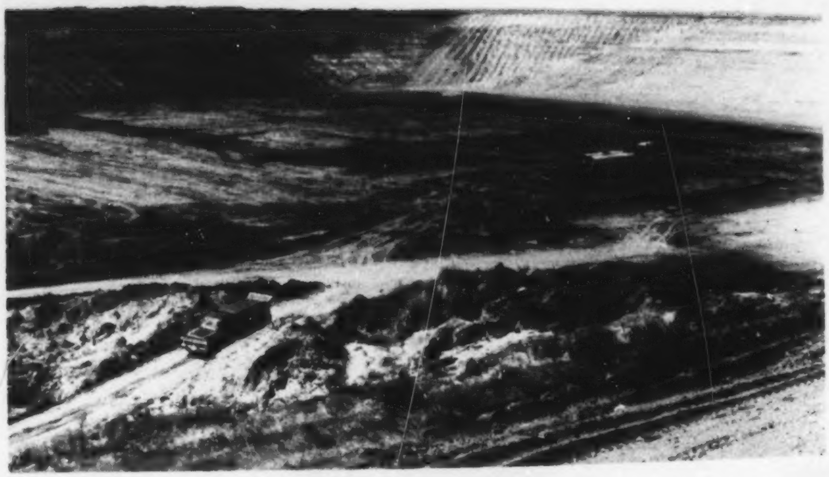


Figure 5-10. Water vehicle used to prepare the soil for compaction.

inches of earth or gravel (to protect the clay liner from erosion or mechanical damage) or it may be mixed in with the soil to form a uniform surface layer. The application rate for the latter is about one lb/ft^2 of soil. Similarly bentonite may be mixed with sand, in a volume ratio of approximately 1 to 8 ($3 lb/ft^2$ bentonite), spread in a layer 2 to 4 inches thick and covered.

A slurry of bentonite (bentonite 0.5% by weight) may be added to existing (filled) ponds to decrease the permeability of the soil or gravel liner. The bentonite settles filling void spaces and effectively sealing the surface.

Bentonites vary in quality. The moisture content of the clay should be less than 20% especially for thin membranes. Wyoming-type bentonite which is finer than No. 30 sieve or well graded if coarser particles are present have proven very satisfactory (Middlebrooks et al., 1978).

For some uses, e.g. canals, bentonite slurry can only be a temporary seal. It is subject to shrinkage, cracking, and erosion from moving water. Also, any calcium in the water will cause a base exchange with the sodium in the bentonite and increased permeability (Bureau of Reclamation, 1963).

5.3 Disposal Facilities With Linings of Admixed Materials

5.3.1 Introduction

Admixes refers to cement-like and asphaltic concrete materials. Construction or installation methods for soil cement, concrete, asphalt concrete, and asphalt panels are discussed in this section.

5.3.2 Soil Cement and Portland Cement Concretes

Soil cement liners can be made from standard or plastic soil cement mixes. The latter contains more cement and water than the former. Best results are obtained when a well graded sandy soil (maximum size 3/4 in) is mixed with the cement. Type V sulfate-resistant cement is recommended. The design mix should be tested by the moisture-density relations test ASTM D558, wet-dry test ASTM D559, freeze-thaw test ASTM D 560 and the permeability tests of E-13 in the Bureau of Reclamation Earth Manual.

Soil cement is placed using road paving methods and equipment. It should not be placed in air temperatures below 45°F. The compacted density should be 98% of the laboratory maximum density. The compaction should proceed so that no more than one hour elapses between the spreading and compacting of a layer. Several stages of the installation of a soil cement liner are shown in Figure 5-11. The surface of a compacted layer must be kept moist by fog spraying if another layer is to be applied. The finished liner should be allowed to cure for 7 days. Soil cement must be sealed. The sealing compounds are bituminous liquids and emulsions sprayed onto the soil cement surface after it has been sprayed with water to reach its maximum water absorption level. This spraying should be done as soon after compaction as practical (Day, 1970).

5.3.3 Concrete and Cement

The details of procedures for construction, subgrade preparation, placing and curing of cement concrete liners may be obtained from the Bureau of Reclamation's Concrete Manual 1975, and from consulting engineers in this field. However, some considerations and procedures are presented below.

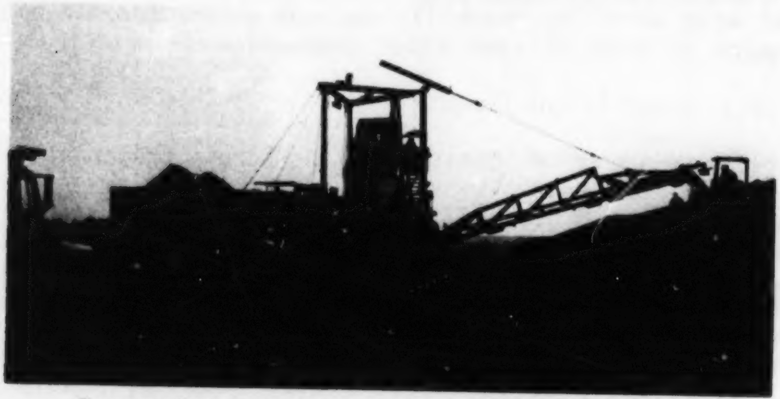
Subgrade preparation is particularly important if there is a possibility of high hydraulic pressures against the liner. A layer of gravel or drainage system should be placed beneath the liner. The subgrade should be well moistened just before placing the concrete. This will help prevent the liner from drying too quickly (Bureau of Reclamation, 1963).

Concrete mixes for pond liners should be plastic enough to consolidate well but stiff enough not to slip on side slopes. A concrete mix with a slump of 2 to 2.5 inches is usually satisfactory. It is important to control carefully the workability and consistency of the concrete; a change of one inch in slump will interfere with the quality and progress of the work. The maximum recommended size of aggregate is 3/4 inch for a liner 2-1/2 inches thick or less. The inclusion of air entraining agents is strongly recommended in areas where the liner will be exposed to freezing temperatures (Bureau of Reclamation, 1975).

The actual placing of the concrete may be done by slip form or the use of a screed. Finishing of liners is not necessary since it is of little useful value in this type of situation. Curing is important. The use of accepted sealing compounds is recommended to produce satisfactory results.

Shotcrete or gunite is cement mixed with sand of maximum size of 3/16 inches, although 3/4 inch aggregate is used for some structural shotcrete. The

Placing machine is custom built to handle 10,000 cu yd of soil-cement a day.



Conveyor boom extends 100-ft to dump soil-cement mix that is . . .

compacted by rollers in stepped lifts of 9-in.

Figure 5-11. Steps in the installation of a soil-cement liner (Brown and Root, Inc., 1978).

relatively dry mix is "shot" through a large flexible hose by pneumatic pressure. Moist curing or use of a curing compound is necessary for shotcrete. Gunite may be used as a liner by itself but generally requires an asphaltic or membrane seal to attain the required permeability (Bureau of Reclamation, 1963).

5.3.4 Asphalt Concrete

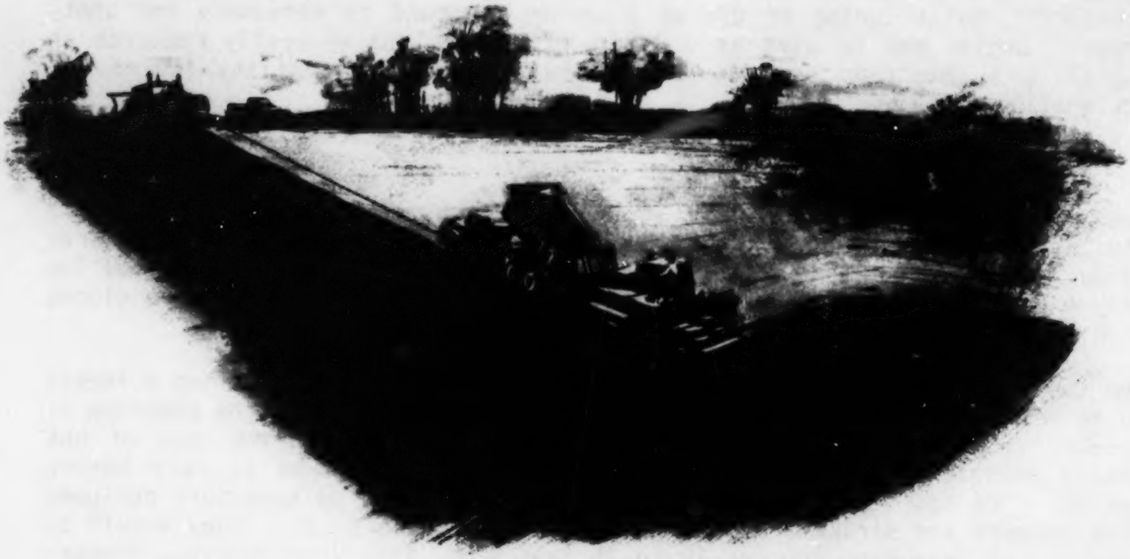
Asphalt concrete for hydraulic structures such as a pond or landfill is similar to paving asphalt concrete but contains higher percentages of mineral filler and asphalt. Side slopes are generally 2:1. The mix does not need the very high stability of paving asphalt but should be stable on the side slopes when hot (Asphalt Institute, MS-12, 1976).

The subgrade should be smoothed by rollers after compacting the top 6 inches to at least 95% of maximum density by ASTM D 1557. Initially, the subgrade is treated with soil sterilant to prevent weed growth. A prime coat of hot liquid asphalt is then applied to the surface and allowed to cure before paving. The hot asphalt concrete mix should be placed by spreaders equipped with hoppers and strike-off plates or screeds (Figure 5-12). They should be capable of producing courses 10 to 15 feet wide, free from grooves, depressions, holes, etc. Ironing screeds used with strike offs and screeds on the spreader should be heated to at least 250°F before starting operations to prevent sticking or tearing of the surface. Placing should be planned to minimize the number of cold joints.

The edges of spreads should be smooth and sloped for 6 to 12 inches to provide a bonding surface with the adjacent spread. Cold sufaces should be heated with an infra-red heater just before forming joints. Asphalt concrete mixtures should be applied to slopes from bottom to top (Day, 1970). Generally, best results are obtained when the side slopes are paved before the floor (Asphalt Institute, MS-12, 1976). The asphalt concrete liner should be compacted as soon after spreading as possible. Ironing screeds, rollers, vibrators or tampers may be used for compaction (Day, 1970). In order to achieve a permeability coefficient of less than 1×10^{-7} cm s^{-1}, a voids content of 4% or less is required (Asphalt Institute, MS-12, 1976). When a liner thickness greater than 3 inches is required, multiple courses should be applied. All joints should be staggered to insure strength and low permeability for the liner as a whole (Day, 1970, pp. 56-59).

5.3.5 Asphalt Panels

Prefabricated asphalt panels require careful planning and workmanship for proper installation. The placement and bonding of the panels should be carefully planned before installation begins. Figure 5-13 shows the installation of asphalt panels in a small canal. The subgrade is excavated, smoothed, rolled and soil applied if necessary. Panels are then placed either butted together or overlapped. Bonding is done with hot or cold asphalt mastic adhesives. Cold adhesives require more time for construction and bonding than do hot adhesives which require on-site heating equipment. The surface to be bonded must be clean and dry. If the panels are butted



Asphalt Concrete May Be Applied By Conventional
Paving Machine If Slopes Are Not Too Steep

Figure 5-12. Placing of hydraulic asphalt concrete liner. Asphalt concrete may be applied by conventional paving machine if slopes are not too steep, as shown in the top photograph (Asphalt Institute, 1966). The lower photograph shows a canal being lined by use of a winch-drawn screed operating transversely up a side slope (Bureau of Reclamation, 1963).

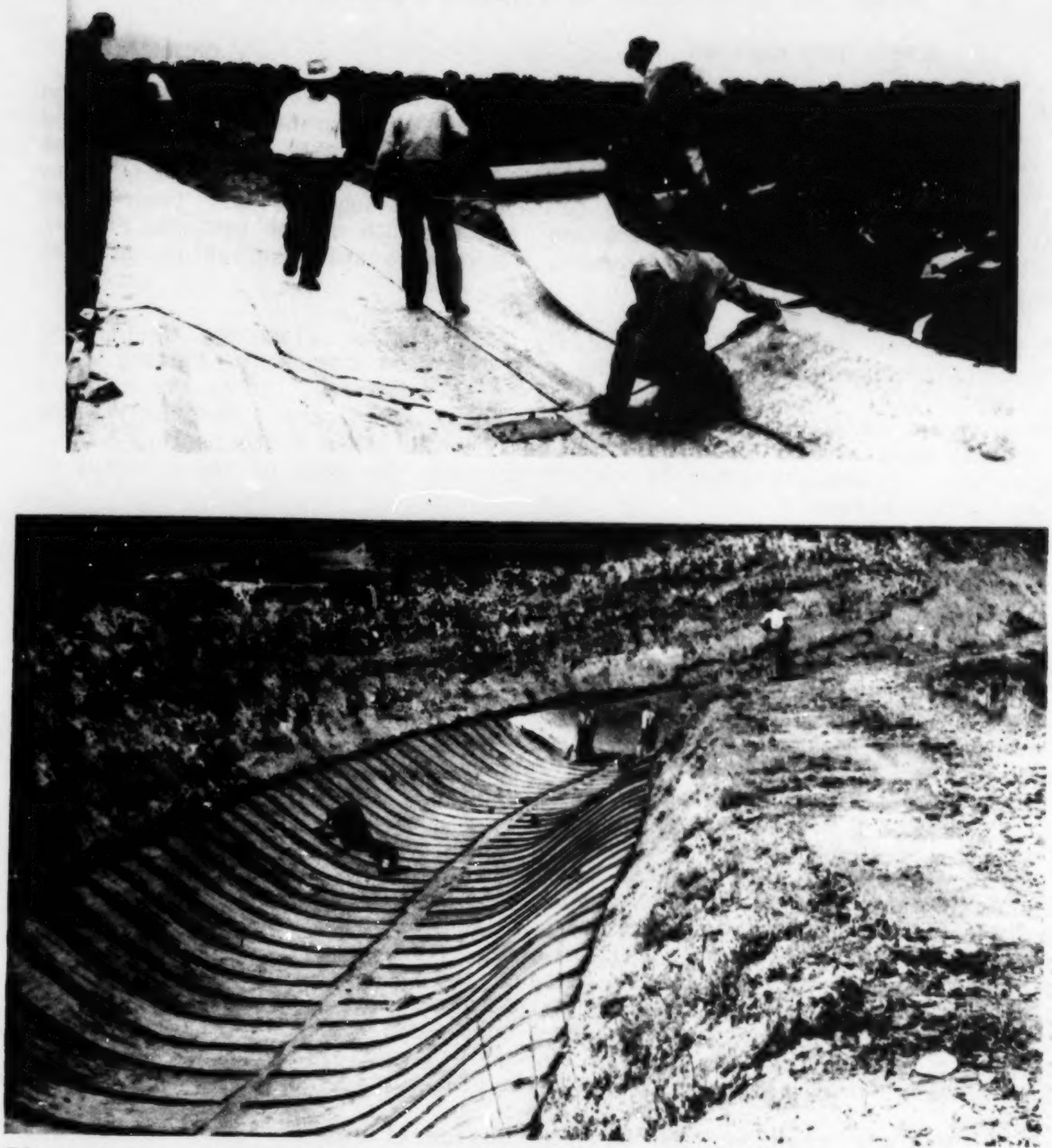


Figure 5-13. Installation of asphalt panel linings in canals. The top photograph shows the placing of lightweight, buried, glass-fiber-reinforced, prefabricated lining and the bottom photograph shows the installation of exposed prefabricated lining (Bureau of Reclamation, 1963).

together batten strips must be cemented over the joints (Asphalt Institute, MS-12, 1976).

5.4 Design and Construction of Flexible Membrane Liner Installations

5.4.1 Introduction

The purpose of this section is to discuss the factors pertaining to the design of systems for waste disposal facilities and to describe the methods and equipment used to line the waste disposal facilities with flexible membrane liner materials. Shultz and Miklas (1980) are conducting a study to identify current methods and equipment used to (1) prepare subgrades for liners, and (2) place liners, particularly membrane liners. Much of the contents of this section and Appendix IV is based upon the results and observations of that ongoing project.

Flexible liner installations generally have similar planning, design and construction components. One of the most important components and one which is common to all flexible liner systems, is the subgrade. It is the subgrade which serves as the supporting structure for these liners. The quality and integrity of the subgrade must be assured if the liner is to perform satisfactorily. Inadequate subgrade support accounts for many of the failures of liner installations.

Equally critical to a good project is the proper installation of the selected liner material over the subgrade. Installation involves numerous steps and planning before the job is begun. There are many experienced installers of liners presently operating in the United States. A partial list of installers is presented in Appendix II. These companies have personnel trained in proper field placement and seaming techniques which have been acquired through installation experience and contact with the liner fabricators and manufacturers. Such experience is needed by the owner of a facility and assures adequate compliance with project plans and specifications to produce an installation that will perform its intended function.

Each of these aspects is discussed in the following sections. Pictures, figures and tables are presented to illustrate or support the discussion of each major aspect. It is important to note that the size of lined impoundments can vary from less than one acre to many hundred. Because of the time and cost considerations, several, if not all, of the constructions steps discussed in this section may take place at the same time. For example, liner placement may be in at one end of the impoundment while the subgrade preparation at the other end of the impoundment continues. Landfills may be lined in modules or phases, making sure the lining is adequately protected during the time between lining installation and waste placement.

5.4.2 Planning and Design Considerations for Membrane Liners

Overall design and planning considerations for lining waste disposal facilities are presented and discussed in Section 5.1. In this section considerations which pertain specifically to flexible membrane liners are discussed in greater detail.

5.4.2.1 Type and Texture of 'In Situ' Soils

In the planning/site selection process, care should be taken to select the best available location for the proposed facility. The classification, relative homogeneity, and relevant physical, mechanical, and chemical character of the 'in situ' soils should be determined. The soils may be tested for Atterberg limits and grain size relative to 'shrink/swell' moisture, density, strength, settlement, permeability, organic material content, clay mineralogy, ion exchange capacity, and solubility. Appropriate soils engineering test methods should be used.

Soils which have high 'shrink/swell' characteristics should generally be avoided. The normal changes in soils which experience clay expansion (wet) and contraction (dry) may act to weaken an earthen structure, both at the bottom and on the sidewalls/berm structures, if the clay is allowed to be alternately wet and dry. Unwanted voids may be generated by repeated 'shrink/ swell' cycles, introducing water into the structure, thus encouraging failure.

The presence of organic material in a soil below a membrane liner can cause a variety of problems. Organic material can generate gases through natural decay processes, and tree trunks and extensive root systems can create voids beneath the liner. If gases are generated beneath a liner, they may collect to the extent that the liner is pushed upward from the subgrade. The phenomena of membrane liner displacement by gases produces the undesired 'whale back' effect where large portions of liner rise up and out of the liquid to be contained (like a balloon), eventually rupturing or requiring rupture to release the trapped gases. The decay of organic material can also create voids which lead to base material slumping, subsequent liner shifting and potential liner failure.

The soluble material in the foundation material beneath a liner can also cause both the gas and void problems. Any acid leakage, however minimal, which could reach a carbonate rich soil, might produce quantities of gas resulting in a catastrophic liner failure. The dissolution of the carbonate might also cause cavities and loss of liner support.

Removal of organic material and the installation of gas vents would be necessary if the soil contains organic material, or if other gas problems are known. The bottom of the impoundment must be sloped upward 2 - 4% minimum to allow gas to reach gas vents.

5.4.2.2 Subgrade Characteristics

The liner subgrade must provide a relatively firm and unyielding support for the liner material. In this sense, the subgrade includes all excavated soil, all engineered fill and all trench backfill. The performance of the subgrade is dependent upon: (1) the loading it is subjected to by the weight of waste applied; (2) the subgrade characteristics and subsequent groundwater changes; (3) slope instability; (4) liner malfunctions; or (5) seismic activity. The main characteristics or relevance for subgrade materials are settlement (stress-strain relationship), consolidation (strain-time relationship), strength, and acid solubility. These parameters are readily determinable by field and laboratory tests. Simpler, less expensive tests which have been previously correlated with these tests are performed during construction to allow a thorough coverage of the subgrade quality. These simpler tests include Atterberg limits, grain size, and compaction tests. Strength and occasionally consolidation tests may be run on the subgrade earthwork, if deemed necessary by the quality control programs.

5.4.2.3 Desired Characteristics of Bottom and Side Surfaces

In most liner installations, the more plane and regular the subgrade side slopes and base are, the easier and more reliable will be the liner installation. The largest particles in the subgrade soil on which the liner is to be placed should be less than three-quarters inch. Large gravel, cobbles, and boulders are to be avoided. Furthermore, the largest particles should be rounded to subrounded rather than angular. Where large particles are present, plan on either removing the larger particles by hand raking or grading at least 3 inches to 6 inches below the desired bottom elevation, and subsequently backfill with material with the desired particle size characteristics, compacting the added material to provide the desired homogeneous base and sides which are free from large particles. In case where subgrade roughness cannot be avoided, a suitable geotextile underlay, e.g. filter fabric should be considered.

5.4.2.4 Location of Bedrock

Carefully consider the alternatives to construction of a lined impoundment when rock removal (through blasting and other procedures) and rock shaping is required. The economic consideration will probably be paramount here, as the cost of working in rock is many times larger than construction activity in weathered rock or loose material. In addition, the potential for large angular particles and irregular surfaces is much greater.

5.4.2.5 Stability of Materials

The importance of utilizing a material with stable characteristics under differing loading and climatic/meteorologic conditions cannot be overemphasized. The reaction of a given soil to changes in stress or moisture content should be considered in the design of a given structure. The selection of side slope angles will also be governed by the ability of a selected material to maintain the selected grades. Generally, a 3:1 or less slope is safe for most materials, although seismic considerations may require flatter slopes. Wave erosion may cause sloughing of the cover soil within the operating liquid level and freeboard zone. This zone should be provided with erosion protection. This zone should be provided with a carefully designed earth cover which takes into account the hydrodynamics of the wave action. Experience with earth dam design has provided us with a good source of practical design solutions for this problem (Bureau of Reclamation, 1973).

5.4.2.6 Drainage Consideration

Surface runoff will be affected by the impoundment. If the impoundment is in the pathway of natural drainage, the diversion drainage systems, overflow structures and later subterranean diversion systems must be planned to handle the water excesses in order to minimize potential damage to the impoundment structure and minimize other adverse impacts. An underdrain system may be required to remove groundwater which accumulates beneath the installed liner through time. Infiltrating water beneath liners/impoundments is particularly common in areas with high subsurface flow, or high groundwater table; the problem must be recognized in advance so that design accommodations can be made if the integrity of the impoundment/liner is to be maintained throughout its projected life. Areas subject to flooding and areas with high water tables must receive special design, construction, operations and maintenance concern.

5.4.2.7 Impoundment Dimensions

The most economical shape for an impoundment is rectangular with straight sides. Curved sides and irregular shapes usually add to the grading and installation costs and increase the number of structural failure points that can occur. Avoid circular impoundments as the grading costs and installation costs for liner materials will be increased significantly along with the construction costs.

5.4.2.8 Wind Direction and Velocity

Design of the pond must take into consideration the prevailing winds. Winds adversely affect the liner in two principal ways, in the form of wave action as the wind impinges on the liner and in the form of lifting action on the slopes in the case of membrane liners. Proper venting of the membrane liner at the top of the slope can mitigate or negate the airfoil effect created by the slope. The placement of weight tubes on the slopes also helps to break up the flow of air across the pond in addition to providing ballast to hold the liner on the slope (Small, 1980).

5.1.2.9 Ambient Temperature

The temperature characteristics of the environment can be a factor in the liner selection process. Of particular significance are temperature extremes and the duration of those extremes. Materials that exhibit superior low temperature resitance to cracking may not be able to withstand the effects of high tempertures. Low temperatures along with strong winds can result in a flex fatigue type failure. Materials that creep at high temperatures may elongate to failure during cycles of high temperature (Small, 1980).

Low temperatures which can cause icing or freezing introduce another set of adverse factors to the structural integrity of the liner. Because of freeze-thaw cycling, the integrity of the subgrade may also be affected.

5.4.2.10 Local Vegetation

In addition to gas problems, vegetation can jeopardize liner integrity as a result of growth. Certain grasses can penetrate flexible membrane liners. Where certain woody vegetation or grasses are evident, soil sterilization with an appropriate heribicide may be required to prevent damage to the liner. Salt grass, nut grass, and quackgrass are examples of local vegetation which mandate soil sterilization. The topsoil layer containing this vegetation should be removed as a part of subgrade preparation. If these grasses are present, soil sterilization should also be automatically included in the construction process. If a soil sterilant is used, polymeric liners should not be placed immediately after application. Time should be allowed for the sterilant to be absorbed by the soil or to lose its volatile components so that it will not react with the liner.

5.4.2.11 Floor Consideration

The floor of the impoundment should not be flat if there is the possibility of gas production beneath the liner. The floor should be designed to slope upward with a minumum grade of 2% from a low point near the center in order to encourage gas movement out from beneath the liner. Since the vent design must provide a permeable material to relieve the gas to the atmosphere, it may also serve as a subdrain. The designer should provide for liquid gathering and release as well as for safe discharge of the vent gases. If the liner is being installed in a landfill in order to capture leachate, a leachate collection system may be required in order to manage the leachate as it forms and to allow the removal of quantities of infiltration water which may enter the landfill after periods of precipitation or snowmelt. Outside grades should be designed to prevent an influx of runoff water into the pond. Cut-off trenches should be used in mountainous areas to prevent washouts.

5.4.2.12 Berm Width Requirements

The width of the containment embankments will be determined by their height and the design side slope; the width of the berm is an optional design factor. The minimum suggested top width is ten feet in order to allow sufficient room for equipment and men to operate during liner installation, to provide room such that anchor trenches can be efficiently installed should they be required, and to facilitate maintenance and repairs throughout facility life.

5.4.2.13 Inflow/Outflow/Overflow Conveyances

The fewer penetrations in a lined impoundment, the greater its probable integrity; thus, if possible, inflow/outflow piping should be designed to go "over the top". If inflow/outflow piping is required, select pipes made of materials which are compatible with the liner type. During installation, soil around the pipes should be well compacted to insure that voids and loose structures are eliminated. If an "over the top" inflow pipe is used, a splash pad may be needed to prevent system damage to the liner.

5.4.2.14 Monitoring and Leak Detection Systems

If monitoring wells are needed, locate them both up gradient and down gradient of the impoundment so that the background quality can be compared with the possibly contaminated groundwater. The down gradient monitoring wells should be designed to monitor groundwater before the groundwater leaves the site facility boundary or emerges into a surface water body. The number of wells is dependent on the size of impoundment, the material stored, the relative need for early discovery of leaking material, and the environmental sensitivity of the local system (EPA-OSW, 1977).

Some hazardous substances to be stored in lined impoundments are potentially so damaging that the regulatory agency may require a leak detection system be installed immediately beneath the impoundment. The system will usually involve two liners; an underliner of clay or other suitable material will be overlain with one to three feet of permeable material. The underliner will slope toward a center low spot either at a point or along a trench which extends the length of the impoundment. A suitable liner material will be placed over the permeable material. If the primary (uppermost) liner leaks, the leaking material will be channelled to a collection point either via the trough or in the centralized low point. The leaking material will be collected, removed, and discarded either back into the reservoir or by other acceptable means.

5.4.2.15 Monitoring Liner Performance

An important output of the planning and design process is a procedure to monitor the performance of the installed liner. The procedure should be relatively simple to perform and produce verifiable results (probably through coupon testing and evaluation and periodic groundwater monitoring). Ideally, the monitoring of liner performance should be in situ, nondestructive, and nondisruptive. Realistically, performance monitoring will most likely involve sampling of soils and waters from selected locations beneath the liner and/or the subgrade. This topic is highly site specific, and as such the factors and procedures differ for each facility.

5.4.2.16 Membrane Liner Coupons

A valuable element of a membrane lined waste impoundment facility is a coupon placement, testing and evaluation program to reveal the condition of the liner and the effects of the wastes on liner physical properties over time. The planning and design process must detail the coupon program. A more comprehensive treatment of this subject is presented in subsection 5.4.7.

5.4.3. Preparation of Subgrade for Flexible Membrane Liners

5.4.3.1 Compaction of Subgrade

Compaction of the subgrade soil is required to provide a firm and unyielding base for most lining materials, be they admix, synthetic membrane, soil, or other. Generally, a fill subgrade is built up in a series of compacted layers, whereas an excavated subgrade is compacted only at its surface. Usually, the minimum compaction of the subgrade material will be specified.

Most liner installations require the density of the subgrade achieve at least a specified percentage of that obtainable by the Standard Proctor Test, ASTM D698, with 90% of Proctor being the most specified relative compaction. Some contracts will specify the compaction equipment which is to be utilized, number of equipment coverages per layer, layer thickness, permissible water content range at placement,and method and location of water addition.

The regularity and texture of the surface of the uppermost layer in the compaction scheme is critical in the liner installation process. A plane surface after compaction is the most desirable one for liner placement but is not always achievable or specified in the contract. In many installations, soil clods or local surface irregularities will be flattened (further compacted) by the overlying weight of the stored material after the impoundment is filled. Further, it is thought that the flexible membrane liners will adjust their shape over any clods so that no detrimental effects will result. Nevertheless, rocks or irregularities with sharp edges should be eliminated from the finished subgrade during the compaction/ construction process even when not specified in the contract if a thin flexible liner integrity is to be maintained.

Within the flexible liner industry, there is a difference of opinion as to how smooth surfaces must be to insure liner integrity. The opinions vary with the liner material. All installers would agree, however, that the smoother the finished surface, the easier the task of flexible liner installation.

5.4.3.2 Fine Finishing of Surface

After compaction has been completed, it is normal to fine finish the surface. Fine finishing is an intensive aspect of subgrade preparation. Depending on the design specifications, various techniques are used. Often, teams of men (generally from two to ten depending on the size of the job) are assigned to scour the surface on both the base and sidewalls, looking for and removing rocks or debris. Men are also encouraged to tamp down any soil which can be manually disaggregated and spread.

The desirability of a smooth surface on the bottom and sidewalls has given impetus to the utilization of various drags to aid in the formation of a regular, flat working surface. Usually, the fine finishing with vibrating rollers and drags will need to be accomplished on a slightly wet surface; thus, water tank trucks are a familiar sight during the fine finishing activities. Occasionally, soil additions are required to bridge surface irregularities if the irregularities cannot otherwise be removed. Sand is useful for this purpose as it is easily compacted.

Figure 5-14 shows examples of subgrade that require additional work before a membrane liner can be placed. Figure 5-15 shows scraper and roller being used to fine finish a subgrade. Figure 5-16 presents examples of suitable subgrade texture prior to placement of a flexible liner.

The control of unwanted grasses and other types of vegetation is accomplished in the fine finishing stage through removal of the layer containing the vegetation and/or the application of a herbicide to the finished slopes and

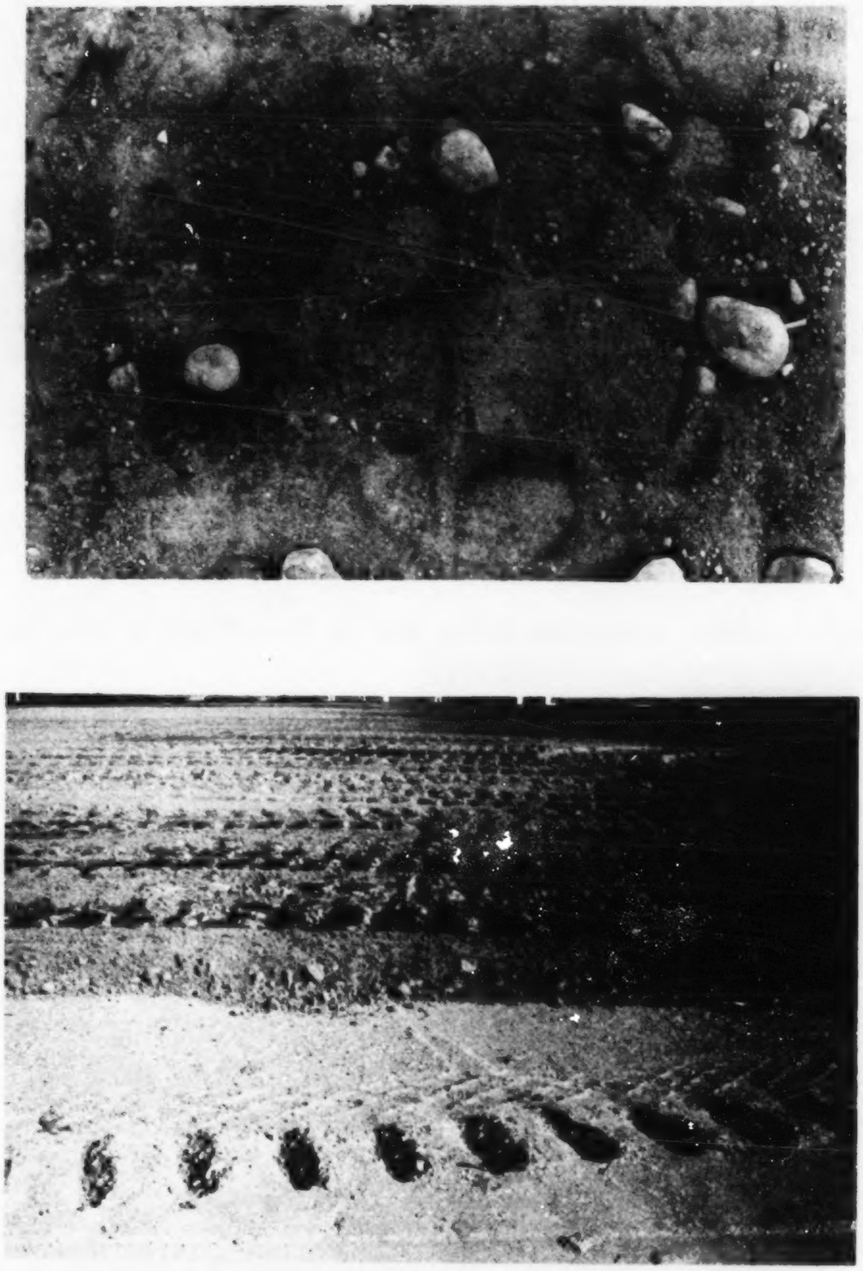


Figure 5-14. Photographs showing various stages of subgrade finishing. These subgrades require further work.

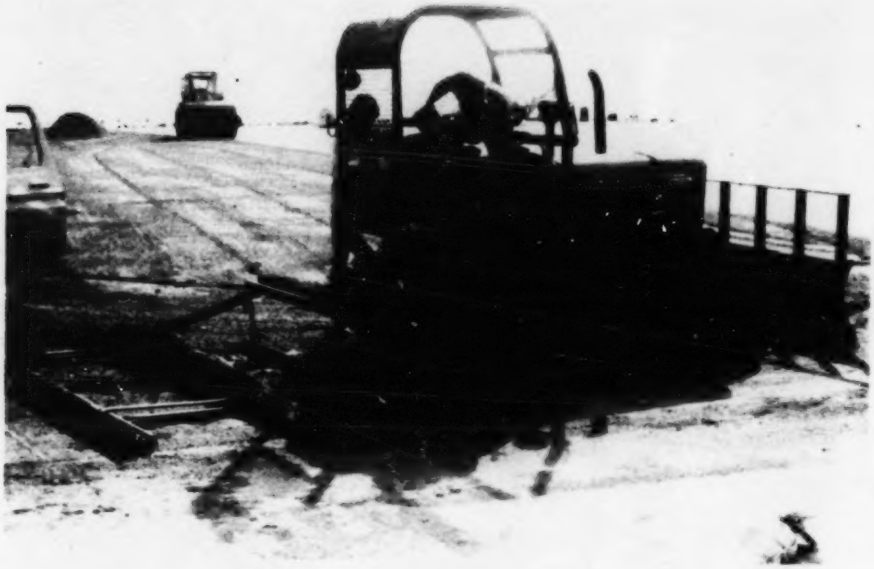


Figure 5-15. Scraper and roller being used to fine finish a subgrade.

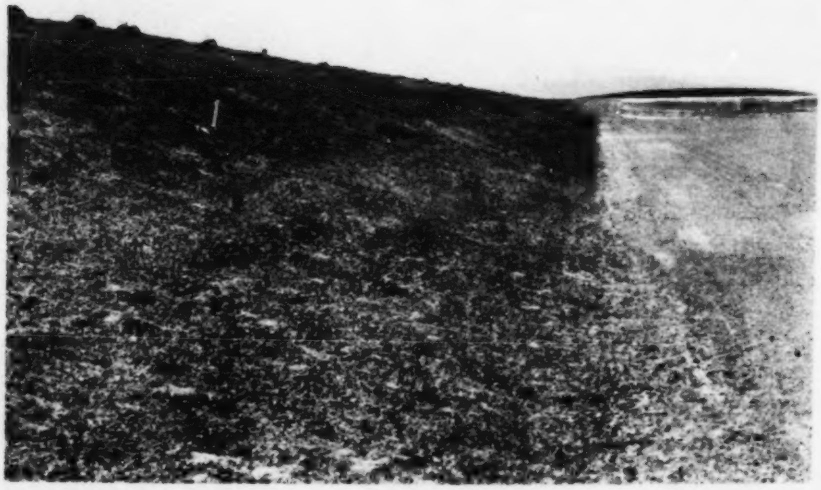


Figure 5-16. Representative subgrade surface texture prior to placement of a flexible liner.

base. The selection of a proper herbicide is critical as some species found in western states are not killed by certain herbicides commonly used in the more humid eastern United States. All fill obtained off-site should be inspected as well to ensure that both germinating and inactive seeds and roots are killed by the application of herbicide.

Generally, it is advisable to wait a few days before laying liner material. Figure 5-17 shows what can happen if a herbicide is not applied properly. The picture shows salt grass penetrating a 30 mil membrane liner. When applying herbicides, proper protection against inhalation and skin contact should be taken.

The activities of excavation, construction, trenching, compaction, fine finishing and liner installation are generally all progressing at the same time on larger jobs. It is desirable during dry weather to apply water or other dust control compounds since the field seaming process is best completed in a dust-free environment.

The fine finishing process is critically dependent on the proper care and control of water. If rain occurs during or immediately after the fine finishing work on a slope, rills, ruts, ravines, etc. may be eroded into the surface. Thus, the expenditure of effort to fine finish slopes and bottom for subsequent membrane liner placement should be curtailed when rainfall is imminent; conversely, the placement of liner material on fine finished slopes should be as soon after completion of 'finishing' as possible to ensure that no surfaces are "lost" to the erosive effects of surface runoff.

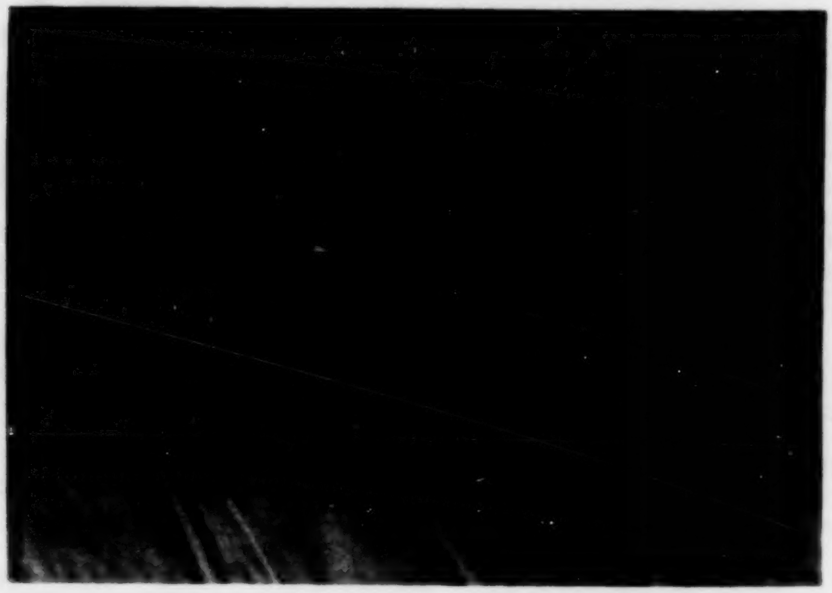


Figure 5-17. Salt grass penetrating a 30 mil flexible liner. Soil sterilization is important prior to placing a liner.

5.4.4 Liner Placement

The installation of flexible membrane liners requires a significant planning effort prior to construction. This planning effort must include consideration of the storage and security of all necessary equipment, installation equipment, manpower requirements, the placement operation, field seaming, anchoring and sealing, quality control, inspection, and protection of placed liners. All of these considerations are discussed in detail in Appendix IV.

5.4.5 Quality Control

A comprehensive quality control program during design and construction is a vital element in the planning, design, and construction, and operation. This program is necesary to assure that the materials used will meet facility requirements and demands, and that workmanship conforms to the installation specifications. A quality control program will provide the operator and owner with confidence that the facility was constructed as planned and will function as intended.

As a minimum, the following items should be considered for incorporation into a quality control program:

- A checklist to assure all facility requirements have been met.
- A specific plan to be used during construction for observation, inspection and testing of subgrade, liner material, factory and field seam quality, installation workmanship, and assurance that the design is followed. Daily records must be maintained of all aspects of the work and all tests performed on the subgrade and liner. For example, air lance seam testing with periodic field seam tensile testing.
- Throughout construction, a qualified auditor responsible to the operator/owner should review and monitor output. This is an ongoing check on the contractor/installer. It generates confidence that the work was indeed done as planned. Changes to planned procedures must be justified immediately and subsequently documented. This can avoid serious conflicts between the owner and design/installation team after the job is completed.

Quality control/inspection programs can result in more effective impoundments by assuring planned review and tracking of all activities comprising the facility design and construction.

There are three major specific areas of quality control concern in a polymer membrane lined impoundment. They are the subgrade, membrane seams, and sealing of penetrations through the liner.

A representative of the primary facility operator, or representative of the ultimate owner of a lined facility, is usually assigned as the quality control agent or enginer on liner installations. The agent will be required to assure that the contractural obligations of the installing contractor(s) are met and that the installation specifications are fully met. Personnel reviewing the design or performing quality control functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the material's use and installation. This includes everything from the liner's compatibility with the material being stored to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

5.4.5.1 Subgrade

A quality control plan for the earthwork portion of the project serves two important functions. First, a uniform density is attained which assures both owner and engineer that the project is constructed as desinged. Second, it provides the data necessary to control costs when field densities are higher than required: this eliminates the possibility of an increased volume of earthwork (Small, 1980). A quality control program should specify the test frequency to ensure accurate and reliable field density data and be tailored to the specific needs and requirements of the project. The factors to consider in establishing a quality control program for earthwork include, but are not limited to, the following:

1. Total project area.
2. Range of fill heights.
3. Number of soil types to be compacted.
4. Consistency of each soil type.
5. Haul distance.
6. Anticipated weather conditions.
7. Method of placement.
8. Method of compaction.
9. Geometry of the site.

It is a generally accepted practice to test each lift of soil placed. The number of tests per lift may very from one to ten tests per 20,000 square feet, depending upon the criteria developed for the project. Soil samples are normally taken and tested to ascertain that the subgrade materials are of the specified classifications and constituency. Measurements of moisture and relative compaction are periodically determined to ensure that the subgrade has the desired firmness. Visual observations of subgrade appearance, earthwork activities and workmanship, lack of vegetation, drain orientation and placement, curb and control of water as necessary, slope characteristics and preparation, and other parameters are conducted on an 'as needed' basis. In some instances, the original design of an impoundment must be modified in the field to accommodate unexpected conditions and unforeseen occurrences. Since membrane liner installations are new to many "earthwork" contractors, advice is often solicited from onsite personnel of the liner installer, fabricator, and/or manufacturer as unforeseen problems arise.

5.4.5.2 Flexible Membrane Liner

The success or failure of the liner installation will depend to a great extent upon the installing contractor's seam credibility. The three basic requirements for credible seam production by heat-sealing are heat, pressure, and dwell time. Job site factors which may influence the field seaming operation include:

1. The ambient temperature at which the seams are produced;
2. The relative humidity
3. The amount of wind;
4. The effect that clouds have on the liner temperature;
5. The moisture content of the subsurface beneath the liner;
6. The supporting surface on which the seam is bonded;
7. The skill of the seaming crew;
8. The quality and consistency of the adhesive; and
9. The cleanliness of the seam interface, i.e. the amount of airborne dust and debris present.

In the case of the adhesive system, the adhesive takes the place of the heat. However, sufficient pressure and dwell time must be applied to create permanent bonding of the seam interface.

Seaming methods differ between liner materials. Cured materials or vulcanized materials such as EPDM and Neoprene are usually sealed with a tongue and groove type seam using gum tape or a two part system. Uncured or unvulcanized material such as CSPE, CPE, and PVC are sealed using solvent, bodied solvent adhesives, or heat. Contact adhesive systems may also be used, however they do not develop the same seam strength as bodied solvent systems. Once the seam has been completed, it should be allowed to stand long enough to develop full strength. An air lance test using 50 psi air directed through a 3/16" nozzle, held no more than 6" from the seam edge may be used to detect any holidays, tunnels, or fishmouths in the seam area. Any imperfections should be repaired as soon as practicable. Once testing has been completed any exposed scrim (in the case of reinforced material) is to be flood coated with the same bodied solvent adhesive. The entire impoundment should be inspected to insure that all the field and factory seams are properly joined, no scrim is exposed and any damage which may have occurred during installation has been repaired. All patches should have rounded corners with the scrim properly flood coated to insure encapsulation.

5.4.5.3 Penetrations

Penetrations of a membrane liner are a significant concern with respect to adequate sealing between the liner and the penetration. Where the penetration is round, stainless steel bands may be used. Screw-type clamps are well suited for small penetrations four inches in diameter or less. For larger pipes, "band-it" type methods may be specified. An extra layer of liner material should be placed between the band and the liner to prevent cutting or abrasion. Flange-type connections offer the most secure type of seal between the liner and pipe penetrations. Flanges should be set in concrete with anchor blocks tack welded to the back of the flange. Care must be taken to insure that the concrete is smooth finished with rounded edges. Additional layers of the liner may be placed over the flange extending to the full edge of the concrete so as to form a gasket and also to prevent abrasion between the concrete and the liner. Once the liner is placed over the flange, an additional layer should be placed on top to form the other half of the gasket seal (Small, 1980).

5.4.6. Earth Covers for Flexible Membrane Liners

Earth covers are commonly placed on polymeric, spray-on, and other membrane liners for two principal reasons:

a. As a protective layer against mechanical, weather, and other environmental damage.

b. As a relatively permeable layer in landfills for the drainage and collection of leachate that is generated in the fill.

It must be recognized that most membrane materials have relatively little structural strength and some are quite sensitive to such environmental conditions as sunlight, heat, ozone, and wind. Some therefore may need cover protection but also care must be taken in selecting and placing a cover on the membrane liner. In service a liner can be exposed to:

- Ultraviolet light which can degrade polymeric materials if not properly compounded.
- Infrared radiation which by heating the liner can cause evaporation of the volatile constituents and oxidative degradation of the polymer.
- Mechanical damage from solid waste primarily during placement in the field.
- Wind, which causes increased evaporation of constituents in some liner compounds, and possibly mechanical damage to the liner itself.
- Wave action in a pond of lagoon.
- Oxygen and ozone.
- Freeze and thaw.
- Hail and rain.

- Animals - hoofed, gnawing, etc.
- Vandalism.

Principal reasons for protection include:

a. To protect the liner from sunlight degradation

b. To prevent hail or wind damage.

c. To prevent liner flotation.

d. To protect the liner from mechanical damage during placement of solid waste or post-construction maintenance.

e. To prevent damage due to vandalism and animals.

It may be necessary to place a soil cover after installation before the filling of the facility can begin.

The need for soil covers for leachate drainage and collection purposes is discussed in Appendix V. This soil cover in addition to being a part of the drainage and collection system will also protect the liner from mechanical damage during placement and compaction of solid waste. Generally these covers are two feet or more in thickness.

Typically, the need for a soil layer as a protective cover is a function of several variables:

- Composition and properties of the liner material.
- Service environment, e.g. exposure, temperature, etc.
- Weather conditions.
- The characteristics of the waste to be contained.
- The planned degree of protection against animals and vandalism.

The manufacturers of PVC liners recommend the placement of an earth cover to protect the liner. Ultraviolet light degrades PVC material by causing chemical changes to occur along the polymer backbone. These changes which can cause embrittlement of flexible PVC liners can be avoided or minimized by compounding the PVC with UV light absorbers and other stabilizers. However, it is recommended that PVC liners be covered regardless of the end use. Other materials, such as CSPE, CPE, EPDM, and elasticized polyolefin are recommended for exposed (noncovered) use. Manufacturers and installers of high density polyethylene and of CSPE question whether the benefit of placing a cover is worth the cost and the risk of potential damage to the liner. All polymeric membranes are susceptible to sun aging if not properly compounded. Thus, the function of a cover in this case is to block out the sun and prevent sun aging.

In addition, a cover is necessary wherever vehicular traffic is anticipated over the liner. In the case of waste impoundment facilities in which hot fluids are introduced, the cover acts to protect the liner from the initial high heat factor and subsequently to insulate the liner from residual heat by decreasing the temperature at the liquid/liner interface versus the temperature of the fluid body. In the case of a lined wastewater treatment impoundment where mechanical aeration is utilized, a cover may be required to mitigate the potential for the liner to be drawn off the bottom or side by hydraulic wave action. On-site weather conditions influence the use of a soil cover or compensating in the design. In extreme climates, such as the northern plains or the desert Southwest, covers are often used to protect against mechanical damage due to freeze-thaw cycles and subsequent ice movement, or sun degradation. Wastewater impoundments in the northern states often become ice covered in winter. Spring thaws can result in ice movement, greatly increasing the chances for damage to an exposed liner.

Other weather conditions often dictate the necessity for special design or performance features. Hail can cause failure of some exposed liner materials, particularly on flat berms where a thermoplastic liner has been installed. Such damage can be easily prevented by the use of a soil cover. Liners exposed to high wind can be stretched and damaged by air lift, if compensations are not made in the design.

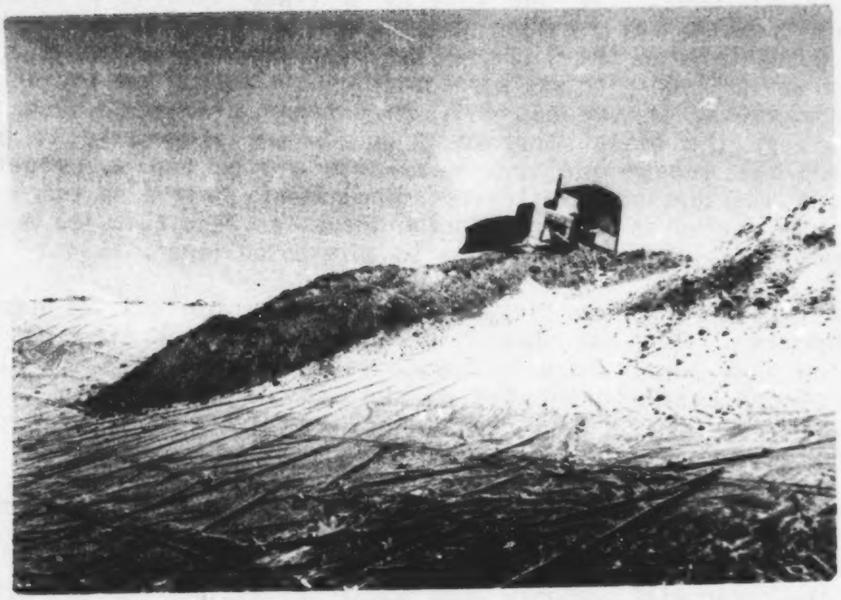
The cover for a liner can also function to reduce the impact of a chemically aggressive or incompatible waste upon the liner. This occurs because of the reduction of the liner surface area which comes in contact with the waste. Furthermore, the cover will probably also reduce the maximum concentrations of waste that contact the liner.

The type of security measures to be incorporated into the operating plan at a lined impoundment will influence the need for a soil cover. For example, if the site is not fenced and wildlife and the public have easy access to the site, then a soil cover will minimize vandalism or accidental damage. Vertical slopes prevent animals from entering the pond. One cannot build economically a fence high enough to keep deer out.

From field experience, it has been found that the maximum side slope ratio which will hold an earth cover over a smooth liner is three horizontal to one vertical. The initial covering should be placed with a light tracked bulldozer. The soil should be spread from a pile and kept at a minimum thickness of 18 inches. It is advisable that the moisture content of the bedding be kept at or below optimum moisture content so that the soil compacts readily with minimum effort. Subsequent layers of protection may be placed in a similar fashion but with larger tracked bulldozers.

The placement of the soil covers, themselves, increases the chance of puncture of the polymeric liner, and once covered, punctures cannot be repaired. The only requirements of a cover material are that it must be free of sharp stone and other objects and that it not be incompatible or reactive with any waste that is to be placed on it. The cover material should be stable and resist sloughing from wave action, not contain large or sharp material which could puncture or damage the lining, and should, wherever possible, be local material to keep the cost low.

Figure 5-18 shows examples of the placing of soil covers on membrane liners.



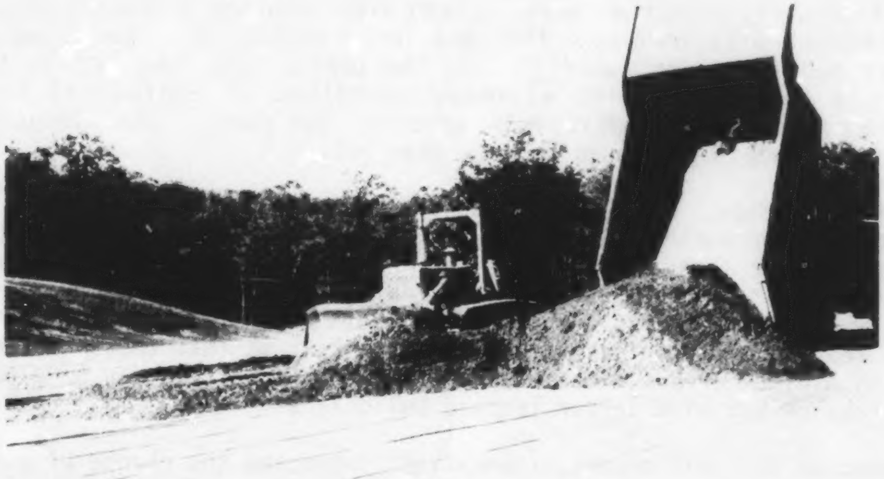


Figure 5-18 Two photographs showing bulldozers applying a soil cover over membrane liners.

5.4.7. Coupon Testing and Evaluation

A critical component of the design, construction, and operation of a membrane lined waste impoundment facility is a coupon placement, testing, and evaluation program. The coupon, a separate small piece of the installed liner, preferably one square foot in area or larger, is used to evaluate the effects of the wastes on the liner material properties over time. To accomplish this testing and evaluation program, the placement of the coupons is an important procedure. Coupon placement should allow for essentially the same exposure and environment to the waste as the installed liner, safe and easy access and retrievability, economical placement, precise location, and precise identification. Thus, the design phase of a lined impoundment facility can contribute greatly to the overall success or failure of a coupon testing and evaluation program. During the construction phase, the accessibility and retrievability factors can be field tested, in addition to the determination of the adequacy of space allocated for coupons. The testing and evaluation program is a long-term ongoing procedure. Depending upon the design function and life of the impoundment, the coupon program will periodically yield information relating to the physical and chemical integrity of the liner on which decisions concerning liner replacement or liner useful life can be made. Exposure periods can range beyond twenty years or can be as short as one year.

5.4.8. Gas Venting

Certain conditions require the venting of gas that may accumulate beneath a liner. If organic matter exists in the soils under the liner, or if natural gas is present in the region, gas production is inevitable. If a pond has a flat bottom, gas will tend to accumulate under the liner. If the pressure is permitted to increase, a membrane liner can be lifted creating a cavern for additional gas accumulation. The higher the membrane bubble is allowed to rise, the more the membrane stretches and the less hydrostatic pressure is available to restrain the membrane. As a result, the membrane floats to the surface.

Venting must also be considered when a fluctuating water table is present immediately below the pond bottom. When the water table falls, void spaces in the soil under the liner are created. Air is then drawn into these voids from the surrounding soil. Conversely, when the water table rises, air which was pulled into the voids is displaced upward. The amount of fluctuation and proximity of the water table to the pond bottom, will dictate the reaction of the membrane to this air pumping mechanism. The need to vent this accumulating gas is best accomplished by providing a layer of uniformly graded sand of which less than 5% by weight will pass the 200 sieve. Also for membrane liners, a geotextile may be used, which allows gas to pass through the fabric's cross-section under a surcharge load. In order for these media to be effective, the bottom of the pond must slope up from its lowest point to the toe of the dike a minimum of 2.5% and the liner must be reinforced with a fabric scrim. The venting medium is carried across the entire bottom, up the side slopes. Venting to the atmosphere is accomplished through gas vents located on the inside slope of the berm, approximately 1 foot down from the crown of the dike. A simplified representation of a gas vent for membrane liners is illustrated in Figure 5-19.

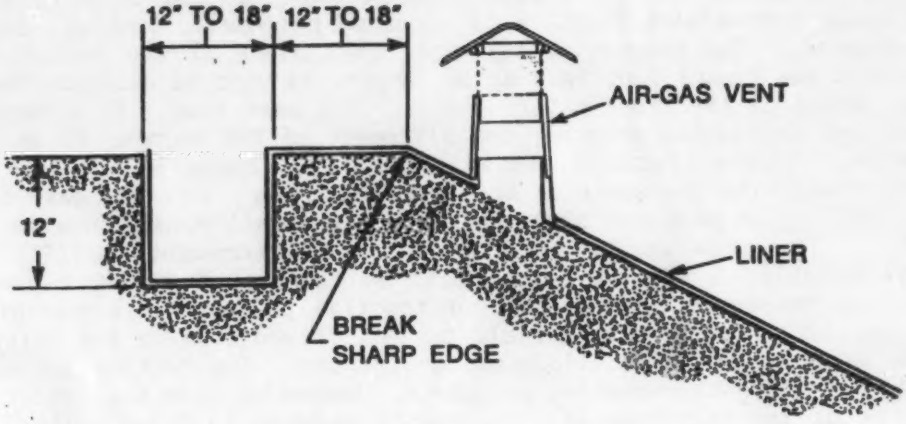


Figure 5-19. A simplified representation of a gas vent for membrane liners.

5.5 Placement of Miscellaneous Types of Liners

5.5.1 Sprayed-on Liners

A basic problem in the placing of this type of liner is to make it pinhole free. Spray-on liners require a more carefully prepared subgrade than other liner types. The subgrade is dragged and rolled to produce a smooth surface free from rough, irregular or angular protuberances. If the surface cannot meet the above criterion, a fine sand or soil padding may be necessary for proper membrane support. The site should be excavated or over-excavated and side slopes flattened to allow for any padding necessary before liner application and for 1 to 3 feet of cover over the membrane (Bureau of Reclamation, 1963, p. 80).

Sprayed-on catalytically-blown asphalt membranes are heated to 200-220°C (392-428°F) and applied at a rate of 1.5 gal/yd^2 measured at 60°F. The high softening point asphalt should not be overheated since this may lower the softening point and change other properties of the material. The spray bar is usually set off to the side of the distributor so that the heavy equipment does not travel over the subgrade or newly applied membrane. To eliminate pinholes, it is recommended that three passes be made at a rate of 0.5 gal/yd^2 each for a cumulative application of 1.5 gal/yd^2 (Asphalt Institute MS-12, 1976). The final membrane is usually about 1/4 inch thick. Sections of membrane should be overlapped 1 to 2 feet. The newly applied hot asphalt melts the underlying layer; both cool to form one continuous liner. The asphalt cools quickly and the next pass with the spray bar may be made immediately after finishing the previous layer. Care should be taken to avoid the accumulation of sand, silt, dust, or gravel on the asphalt between applications. Foreign materials on the membrane prevent proper bonding of layers and may cause pinholes to form.

The property of rapid cooling and hardening also presents some problems in applications. Skill and organization are required to prevent freezing of asphalt in the lines. Spray bars should not be turned off for more than one or two minutes at a time. All pumps, lines and bars should be cleaned with air or distillate after each spraying operation (Day, 1970).

Asphalt emulsions are sprayed at ambient temperatures (above freezing), usually onto a supporting fabric of jute, glass or synthetic fiber. A continuous membrane forms after the emulsion breaks and the water evaporates. Several light applications are used, not only to avoid pinholes, but to allow drying between coats to avoid porosity due to entrapped water.

Asphalt membranes are usually covered to protect them from mechanical damage. Cover materials are usually earth or graded earth and gravel. Membrane damage and leaks can occur from poor application or choice of cover material. Blading the cover frequently folds the top of the membrane and should be avoided. Rocks can tear or gouge the liner. Cover materials should not be applied if the temperature is below 32°F since the membrane may rupture from the operation (Day, 1970). Placement of a fine grained soil cover by draglines should be done on the floor first then from bottom to top of the side slopes. Coarser materials may then be appllied. (Bureau of Reclamation, 1963, pp. 82-83).

5.5.2 Placement of Soil Sealants

Asphalt emulsions may be injected into the subsurface. Special equipment is used to inject the liquid six inches below the surface to form a continuous membrane about 1/2 inch thick.

5.5.3 Placement of Chemisorptive Liners

Chemisorptive liners vary in form and type. Some are soil sealants, liquids or powders, which are applied using methods similar to those used for bentonite or sprayed-on liners. Others are pozzolanic or cement-like. These are installed and constructed following procedures similar to those used for asphalt concrete or cement. Individual manufacturers or producers should be addressed with questions concerning this class of liners.

5.6 Liners and Leachate Management for Solid Waste Landfill

5.6.1 Environment of the Liner in a Sanitary Landfill

The environment in which a liner must function will ultimately determine how well it can serve for long periods of time. The situation of a liner in a sanitary landfill is represented schematically in Figure 5-20. Some of the conditions at the base of a landfill should have no adverse effect on life expectancy of a given material, whereas other conditions could be quite deleterious. The effects can be different for different materials. Some important condiditons that exist at the bottom of a MSW landfill in the

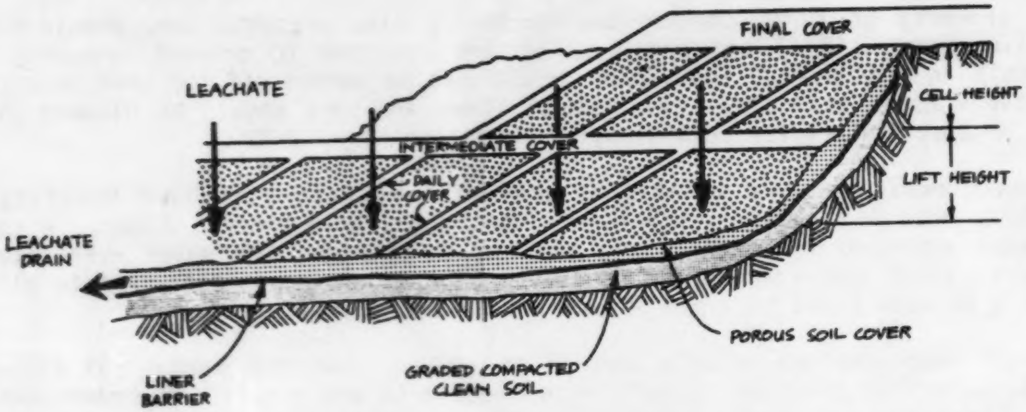

FINAL COVER
LEACHATE
CELL HEIGHT
INTERMEDIATE COVER
DAILY COVER
LIFT HEIGHT
LEACHATE DRAIN
POROUS SOIL COVER
LINER BARRIER
GRADED COMPACTED CLEAN SOIL

Figure 5-20 Schematic drawing of a lined sanitary landfill (Haxo, 1976).

proximity of the liner and that may influence the life of a liner are:

1. The barrier is placed on a prepared surface that has been graded, to allow drainage, land compacted and is presumably free of rocks, stumps, etc., but that may settle to cause cracking of hard liners. A brittle or weak material might fall.
2. Anaerobic condition with no oxygen to cause oxidative degradation.
3. No light, which normally degrades many polymeric materials.
4. Generally wet-humid conditions, particularly if leachate is being generated regularly, that could result in the leaching of ingredients from a liner.
5. Cool temperatures of 40 to 70°F normally, although high temperatures can be generated within the fill if aerobic decomposition takes place.
6. Generally acidic conditions from the leachate due to presence of organic acid.
7. High concentration of ions in the leachate that may exchange with clay soil and increase permeability.
8. Considerable dissolved organic constituents in the leachate that may swell and degrade some of the organic material liners.
9. Only modest head pressure, since drainage above the liner is designed to take place continually. A porous soil is placed on top of the liner before refuse is placed.

10. The presence of the gases, carbon dioxide and methane, generated in the anaerobic decomposition of the refuse. The carbon dioxide is probably dissolved in the leachate and contributes to its acidity. It may cause mineralization of the soil in the area of the liner.

The effects of these environmental conditions will differ on the various barrier materials. However, it appears at present that mechanical failure during installation or during operation of the fill due to settling of the soil may be the most significant source of failure of a liner.

5.6.2 Estimating Leachate Volume

The volume of leachate produced at a landfill site is primarily a function of the amount of water that flows through the refuse; in general, the more that flows through the refuse, the more pollutants will be leached out. Precipitation is a key factor affecting the volume of leachate produced; thus, in regions of moderate-to-heavy rainfall, leachate generation can be significant. For the designer of landfill leachate collection systems, however, a qualitative assessment that "significant leachate will be produced at this site" is not sufficient. What is needed, rather, is a tool for predicting with a reasonable degree of accuracy the quantity of leachate that a given landfill can be expected to produce under a number of different scenarios. Fortunately, within the last several years, such a tool has evolved, based on a water balance method developed by Thornthwaite and Mather (1955) in the soil and water conservation field. A computer model has been developed to simulate hydrologic characteristics of landfill operations (Perrier and Gibson, 1980).

The water balance method is a kind of mathematical accounting process which considers precipitation, evapotranspiration, surface runoff, and soil moisture storage, all of which have a bearing on the extent to which infiltration can be expected to occur after a rain. Since infiltration is the major contributor to leachate generation, knowing how much can be expected under a given set of site conditions will provide the designer with valuable information on which to base his recommendations. Such recommendations might specify the soil types, drainage grades, plant species, or cover thicknesses required to minimize or preclude leachate production. Similarly, leachate sumps, risers, pumps, and treatment facilities can also be more rationally engineered once a water balance calculation has been made.

Three factors are of critical importance in a water balance calculation: soil moisture storage, evapotranspiration and surface water runoff. The first is critical because a cover soil that has exceeded its field capacity (the maximum amount of water a soil can retain in a gravitational field without downward percolation) becomes a source of infiltration to the refuse which may eventually lead to leachate production. Ideally, efforts by the design engineer should be directed to ensuring that the cover soils and other landfill features are selected and installed so as to keep the soil moisture storage below field capacity. Assuming there is no groundwater infiltration or other source of excess liquids, leachate production should not occur. Obviously, some hydrologic regimes such as high rainfall and low evapotranspiration make it uneconomical to achieve this condition at all times; emphasis must then be shifted to determining how much leachate is apt to be produced and what control-recovery-treatment options can be employed.

The amount of water that can be added to solid waste before reaching field capacity depends on the moisture content of the waste at the time of placement in the landfill. Moisture content at time of placement is not a constant, but a function of waste composition, density and climatic conditions. However, as a rule of thumb, moisture content of the wastes at the time of placement has been found to range from 10 to 20 percent by volume (Fenn et al, 1975).

TABLE 5-4
MOISTURE CONTENT OF REFUSE[a]
(Average Values)

Refuse at	Percent by volume	Equivalent inches H_2O/ft of refuse	Equivalent gallons H_2O/yd^3 of refuse
Placement	10-20%	1.8"	30
Field capacity	20-35%	3.6"	60
Saturation[b]	--	6.6"	110

[a] Adapted from: Fenn et al., 1975.

[b] Based on a 0.4 porosity for refuse.

As Table 5-4 indicates, refuse has a large capacity to absorb moisture before leachate is produced. Leachate production will not occur at rates equal to infiltration of rainfall until saturation is exceeded, a condition significantly above field capacity. However, leachate production can occur by channeling, a process by which net infiltration flows through openings or channels within the refuse before the field capacity of the fill is reached.

The second most important variable, evapotranspiration, represents the amount of water present in the soil that is lost to the atmosphere from a given area through direct evaporation from the soil and transpiration from plant tissues. When soil moisture is at or near field capacity, evapotranspiration occurs at its maximum potential rate. However, as soil moisture approaches the wilting point (the moisture content below which moisture is unavailable for withdrawal by plants), the amount of water available begins to restrict the rate of evapotranspiration, resulting in reduced actual water losses. The water balance process takes this effect into account. While rates of evapotranspiration for different parts of the country have been developed by Thornthwaite and Mather (1964). Their method may not provide the best estimate for all areas of the country. Thus, the design engineer has to evaluate Thornthwaite's figures versus other evapotranspiration data that could be applied to each particular area of interest.

The third parameter of major importance is surface runoff, i.e. that portion of rainfall which will run off the site in lieu of entering the cover soil. Variables affecting runoff include intensity and duration of rainfall, existing soil moisture, soil permeability, slopes, and type of vegtative cover. Runoff can be calculated using empirical runoff coefficients commonly used to design surface water drainage systems. By multiplying the coefficients by the mean monthly precipitation, a "mean monthly surface runoff" can be calculated.

Details on the actual calculations involved in using the water balance method are presented in the appendix to an October 1975 EPA report (EPA-SW-168). In brief, the basic equation for determining the amount of percolation anticipated at the given site is as follows:

$$PERC = P - R/O - ST - AET$$

where,

PERC = Percolation, i.e. the liquid that permeates the refuse.

P = Precipitation for which the mean monthly values are typically used.

R/O = Surface runoff

ST = Soil moisture storage, i.e. moisture retained in the soil after a given amount of accumulated potential water loss or gain has occurred.

AET = Actual evapotranspiration, i.e. actual amount of water loss during a given month.

In using the water balance method to quantify the volume of leachate produced, special field conditions at landfill sites should be considered. Variations in cover depth and the absence of vegetation in some areas of the site will influence leachate production. More percolation thus occurs during the operational phase due to such factors as absence of vegetation, shallow depths of intermediate cover, surface cracks and lack of adequate drainage. As a result, leachate may be produced sooner and in greater volume than was predicted by water balance calculations based on a completed landfill. Another special condition that can result in a greater production of leachate than was predicted by the water balance method is irrigation of the completed site for a specific use such as a park or agricultural area. Since the irrigation required to supply evapotranspirative demands of the growing vegetation is not totally efficient, percolation can be significant and hence leachate production can result. An additional field condition that can have an impact on the water balance calculations is the presence of frozen ground and/or snow accumulation. Such a condition reduces the infiltration of the precipitation during winter months with the net effect on the water balance of decreasing percolation and hence the quantity of leachate produced.

To illustrate the application of the water balance method in a variety of climatic conditions, Table 5-5 summarizes data for the key water balance parameters in three regions of the United States: Midwest, Southeast, and Southwest. As the table indicates, the range of values for percolation of moisture into refuse can vary widely depending on whether the site is in a humid climate such as that found in the Midwest, or an arid climate, such as that of Los Angeles.

Once the designer has estimated by means of the water balance method the quantity of moisture that will percolate into the refuse, he is in a position to make a decision concerning the type and size leachate collection facilities. Applications of the water balance method to landfills in a broad range of climatological conditions in the continental United States has shown a range of percolation rates of 15 inches per year to 36 inches per year (assuming proper covering, vegetation, and drainage of the completed landfill surface). These values provide a rule of thumb for use by the designer in sizing leachate collection systems.

The major advantage of the water balance method is its flexibility in allowing for modification of various input variables. This enables designers to compare the effectiveness of alternative control techniques by simply "running" the water balance model for each management plan. When used in conjunction with data on leachate quality and probably water quality impacts, the water balance is an extremely effective tool.

Figure 5-21 illustrates the factors influencing percolation that may be manipulated using the water balance method as a leachate management tool; thus, by increasing several of the water balance variables, leachate generation can be precluded. As shown in Figure 5-22, surface runoff, soil moisture storage, and evapotranspiration - key parameters in the water balance equation - can be readily increased, thereby reducing percolation of liquid into the wastes. Surface runoff can be enhanced by (1) increasing drainage gradients, (2) selecting more impermeable cover soil, (3) using a thicker and denser cover soil, (4) utilizing synthetic membranes, (5) adding soil conditioners (chemicals, bentonite, etc.) to render the existing cover soil less permeable, and

TABLE 5-5 SUMMARY OF WATER BALANCE CALCULATIONS[a]

	Local soil conditions	Precipitation, mean annual cm (in)	Surface runoff coefficient	Percolation mean annual, cm (in)	Percolation, maximum monthly, cm (in)
Cincinnati, Ohio	Clay Loam	102.5 (40.4)	0.17	21.3 (8.4)	6.6 (2.6)
Orlando, Florida	Sandy Loam	134.2 (52.8)	0.075	7.0 (2.76)	2.5 (1)
Los Angeles, California	Silty Loam	37.8 (14.8)	0.15	0	0

[a]Source: Fenn et al., 1975.

(6) implementing a good maintenance program for graded surfaces. Like surface runoff, potential soil moisture storage can be increased by using thicker cover soil and by employing silt and clay cover. Selecting highly evapotranspirative vegetation that is tolerant to landfill conditions enhances evapotranspiration. Landfill slopes must be graded to enhance runoff while minimizing erosion. The final surface of a landfill should be sloped sufficiently to prevent water from pooling over the surface (a minimum slope of 2% is recommended).

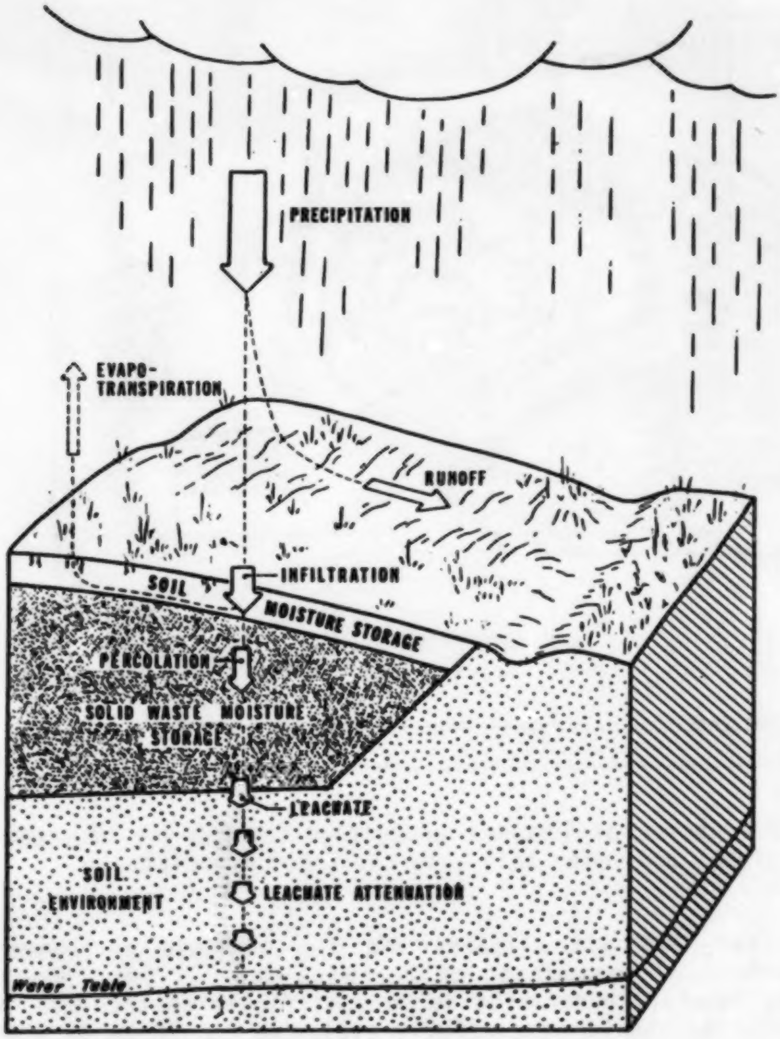

PRECIPITATION
EVAPO-
TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
PERCOLATION
SOLID WASTE MOISTURE STORAGE
LEACHATE
SOIL ENVIRONMENT
LEACHATE ATTENUATION
Water Table

Figure 21 Percolation through solid waste and natural attenuation of leachate by the soil environment. (Source: Emcon Associates)

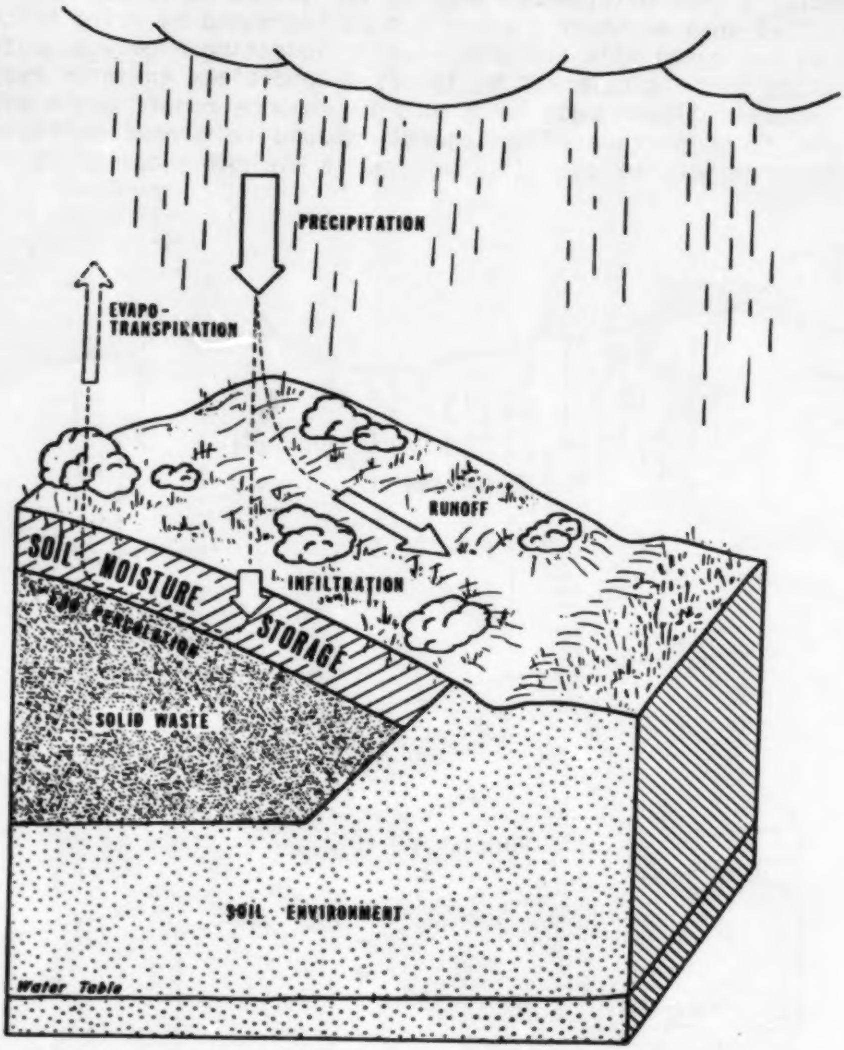

PRECIPITATION
EVAPO-TRANSPIRATION
RUNOFF
SOIL MOISTURE STORAGE
INFILTRATION
PERCOLATION
SOLID WASTE
SOIL ENVIRONMENT
Water Table

Figure 5-22. Preclusion of leachate production through use of proper drainage grades and cover soil (Source: Emcon Associates).

As noted earlier, not all climates and hydrogeologic environments enable practical/economical prevention of leachate generation. Thus, in humid climates where leachate generation is more difficult to preclude, the hydrogeology of the site should be carefully evaluated to determine the potential for natural inhibition of leachate production. At sites where the hydrogeologic conditions are incapable of minimizing the impact of leachate on underlying ground water, leachate collection facilities should be employed. Design criteria for such facilities are discussed in the next section and Appendix V.

5.6.3 Transmissivity of Leachate

When the infiltration of precipitation and other sources of water applied to the landfill surface exceed the combined effects of runoff, evapotrasnpiration, and soil moisture storage, leachate will be produced in the landfill. This net inflow to the landfill, termed percolation on Figure 5-21, is absorbed by the waste until the field capacity of the fill is reached, field capacity here defined as the maximum amount of moisture a soil or solid waste can retain in a gravitational field without producing a continuous downward percolation (Fenn et al., 1975). Thereafter, percolation into the fill will accumulate as leachate at the base of the fill or discharge to the soil-groundwater regime beneath the landfill (see Figures 5-23 and 5-24).

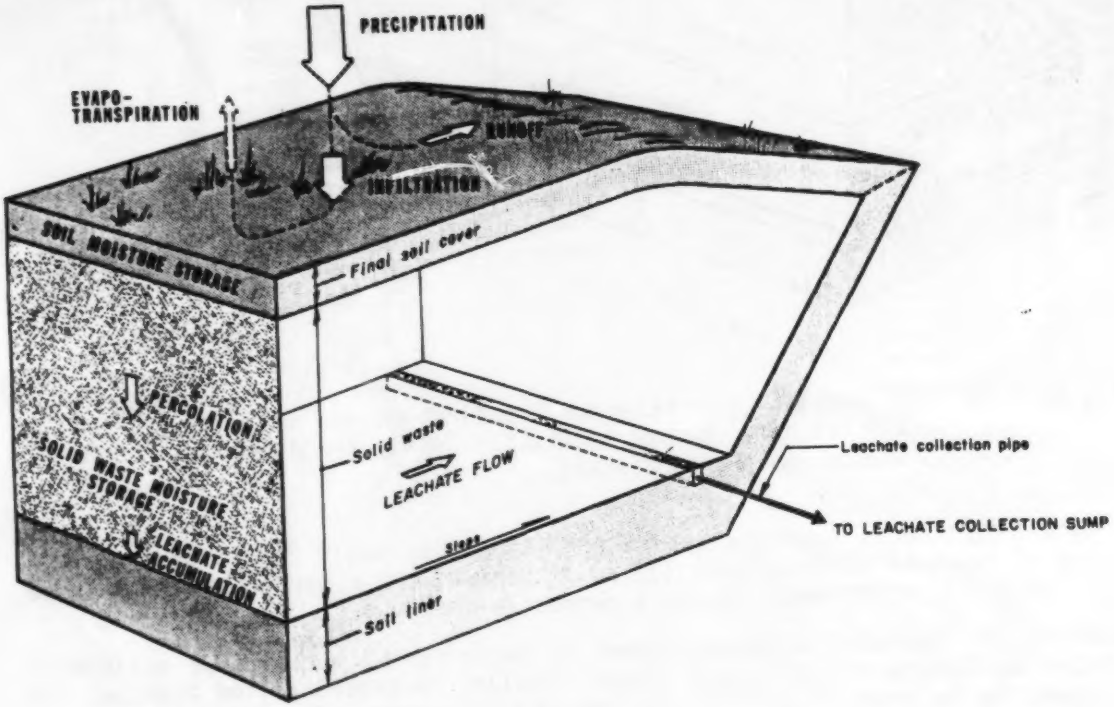

PRECIPITATION
EVAPO-TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
Final soil cover
PERCOLATION
SOLID WASTE MOISTURE STORAGE
LEACHATE ACCUMULATION
Solid waste
LEACHATE FLOW
Slope
Soil liner
Leachate collection pipe
TO LEACHATE COLLECTION SUMP

Figure 5-23 Accumulation, containment, and collection of landfill leachate (Source: Emcon Associates).

When percolation occurs in a landfill located within a containment environment of natural soil, constructed soil liners, or manufactured membranes, leachate will accumulate in the fill. Eventually, the leachate level will rise until (1) the head created on the base of the landfill results in an unacceptable rate of discharge (albeit slow) through the liner, or (2) it threatens to discharge to the ground surface. Both conditions require the removal of leachate to relieve the hydraulic head.

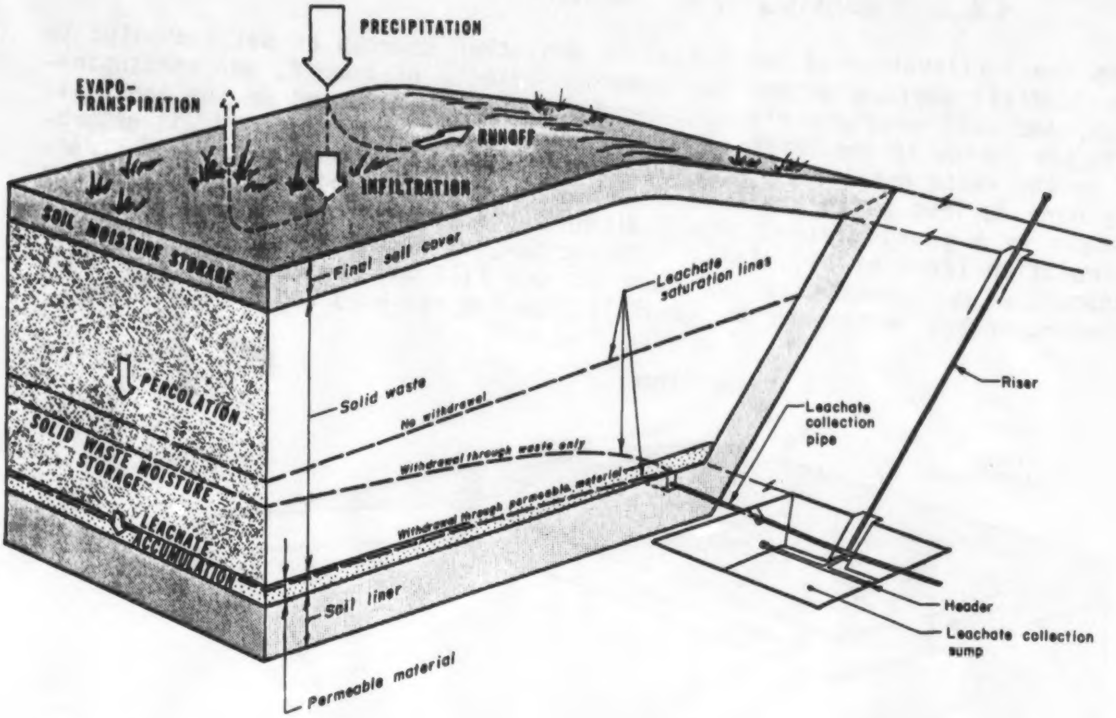

PRECIPITATION
EVAPO-TRANSPIRATION
RUNOFF
INFILTRATION
SOIL MOISTURE STORAGE
Final soil cover
Leachate saturation lines
Solid waste
No withdrawal
Withdrawal through waste only
Withdrawal through permeable material
PERCOLATION
SOLID WASTE MOISTURE STORAGE
LEACHATE ACCUMULATION
Soil liner
Permeable material
Riser
Leachate collection pipe
Header
Leachate collection sump

Figure 5-24 Accumulation, containment , collection and withdrawal of landfill leachate showing saturation levels for different conditions (Source: Emcon Associates).

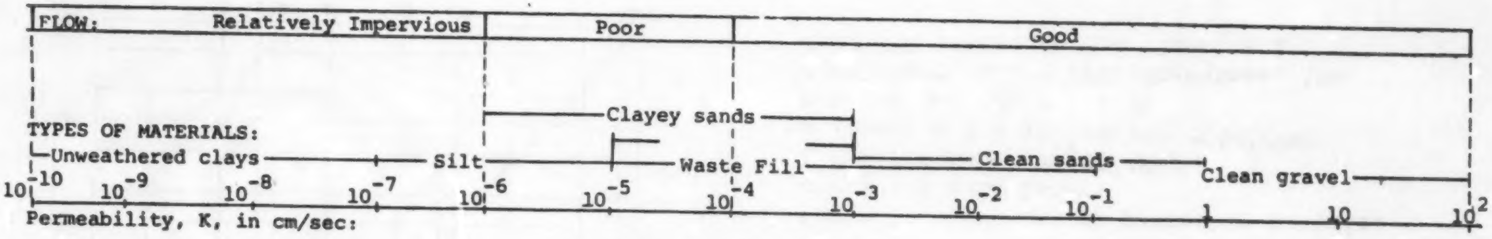
Figure 5-23 shows leachate saturation lines that would result under conditions of leachate accumulation: (1) no withdrawal (2) withdrawal through waste fill only. (3) withdrawal through a permeable medium.

Removal of leachate is accomplished by draining to a leachate collection system consisting of perforated pipes installed in gravel-filled trenches and discharging to sumps from which the leachate is pumped. The rate at which the leachate is removed is directly related to the permeability of the media through which the leachate must flow to the collection system. The permeability and porosity (percent of voids of potential fluid storage) of various soil materials and municipal waste fill are shown on Figure 5-25.

When the geohydrologic conditions beneath the fill require minimization of the leachate head, leachate removal to sumps can be enhanced by the placement of a highly permeable material such as sand over the base of the landfill.

Figure 5-26, based on a flow net solution, provides a method of determining the maximum head that will result in a medium given the permeability, spacing of leachate collection pipes, and percolation rate into a saturated fill. The analysis assumes gravity flow to a water surface in the collection pipe maintained below the base of the fill and a uniform daily percolation rate to

PERMEABILITY, POROSITY AND DRAINAGE CHARACTERISTICS OF MATERIALS



a) DRAINAGE CHARACTERISTICS:

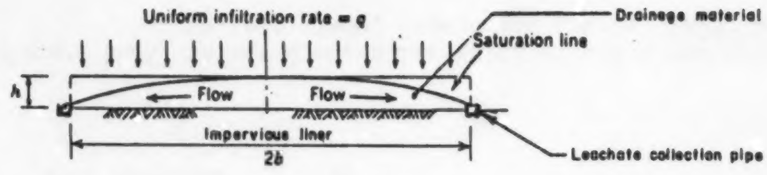
b) AVERAGE PERMEABILITY VALUES FOR VARIOUS MATERIALS:

	COEFFICIENT OF PERMEABILITY	
TYPE	cm/sec	ft/day (calc)
very fine sand	5×10^{-3}	10
fine sand	2×10^{-2}	50
concrete sand	2.0×10^{-2}	50
fine to medium sand	5×10^{-2}	150
medium sand	10^{-1}	250
medium to coarse sand	1.5×10^{-1}	400
gravel and coarse sand	3×10^{-1}	850
clean gravel	10	3.0×10^{4}
concrete gravel	25	7.0×10^{4}

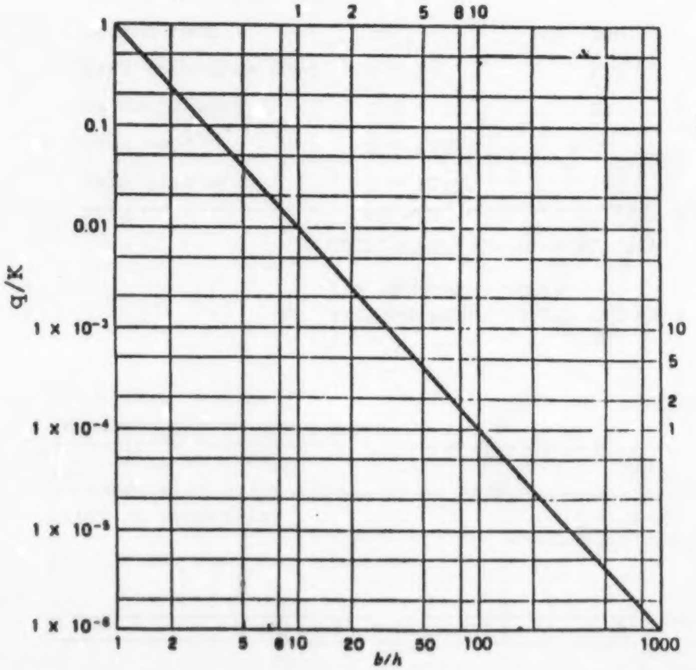
c) RANGE OF POROSITY VALUES FOR VARIOUS MATERIALS:

TYPE	Porosity %
clay	45 - 55
sand	35 - 40
gravel	30 - 40
sand and gravel	20 - 35
municipal waste	30 - 40

Figure 5-25. Selected characteristics of soils and waste fills (Cedergren, 1967; Davies and DeWiest, 1966; Freeze and Cherry, 1979; Sowers, 1979; Todd, 1959).


Uniform infiltration rate = q
Drainage material
Saturation line
h
Flow
Flow
Impervious liner
2b
Leachate collection pipe

(a) Cross section of landfill surface



(b) Uniform infiltration rates vs. b/h for drainage material

For leachate flow conditions represented in Fig. a, the following equation approximates the flow net solution:

$$q/K = \left(\frac{h}{b}\right)^2$$

WHERE:
q = uniform infiltration rate
K = coefficient of permeability
h = head of leachate above impervious liner
b = width of area contributing to leachate collection pipe

EXAMPLE 1.

For waste overlying the liner; with collection pipes at 200' interval spacings:
q = 2"/month = .00548'/day
K (wastes) = 10^{-3} cm/sec = 2.83'/day
b = 100' and $q/K = 2 \times 10^{-3}$
from chart; b/h = 20; therefore, the head (h) acting on the liner = 5'

EXAMPLE 2.

For a 1' thickness of permeable material overlying soil liner:
q = 2"/month = .00548'/day
K (sand) = 2×10^{-2} cm/sec = 50'/day
b = 100' and $q/K = 1 \times 10^{-4}$
From chart, b/h = 100; therefore, the head (h) acting on the liner = 1'

Figure 5-26. Determination of leachate head on impervious liners using flow net solution (Cedergren, 1967). Figure (b) is a log-log plot with subdivisions shown on the right and top of graph.

the withdrawal saturation line. Example calculations are also presented on Figure 5-26.

5.6.4 Leachate Collection System Network

A leachate collection system generally consists of strategically placed perforated drain pipe bedded and backfilled with drain rock. The pipe can be installed in a trench or on the base of the landfill. The system can be installed completely around the perimeter of the landfill or a complex network or grid of collection pipes can be installed - the latter being used when the areas involved are very large and/or the allowable head buildup is quite small (see Sec. 5.7.3 Transmissivity). The collection system is drained to a sump or a series of sumps from which the leachate is withdrawn. Appendix V discusses in detail the layout, sizing, installation, and selection of pipe material for leachate collection systems. A series of charts and tables are presented for use in the design and analysis of the leachate collection system.

The spacing of leachate collection pipes will influence the maximum head of leachate on the base of the fill, given a uniform rate of leachate percolation to a saturated fill and the permeability of the medium through which the leachate is withdrawn. The configuration of the collection pipe network varies depending on the head allowed over the landfill base liner: the greater the allowable head, the greater the pipe spacing. As a minimum, the leachate collection system should extend completely around the perimeter of the site to provide absolute control of the level to which leachate can rise on this critical boundary.

An interior grid system becomes necessary if the leachate head on the base of the fill must not exceed a specified value. The slopes and spacing of the interior grid pipes are controlled to a large degree by the minimum base slope of one percent. Placement of a layer of permeable material over the base of the fill, coupled with the use of an interior collection pipe grid, may be necessary in extreme cases where the development of a leachate head cannot be tolerated.

5.6.5 Leachate Withdrawal and Monitoring Facilities

Landfill leachate control systems must include facilities for (1) the monitoring of leachate levels at the base of the landfill and (2) the withdrawal of leachate to prevent buildup of a fluid level that would promote unacceptable migration of leachate from the landfill.

The current state-of-the-art in landfill design uses sumps or excavated basins located at low points on the base of the landfill to which a leachate control system discharges. A riser pipe extending from the sump to the ground surface or to the surface of the fill provides the means for removing the leachate from the sump in addition to providing a "well" in which leachate levels can be measured. Leachate sumps are filled with drain rock that provides the necessary storage capacity (pore space) while also presenting transmissibility characteristics necessary to produce flow to the withdrawal pump at a rate adequate to maintain the gravity flow from the collection system.

The riser pipe is perforated or slotted along the section immersed in the drain rock filled sump and may be connected to a perforated header pipe in the sump to allow a higher rate of flow to, and withdrawal from, the riser pipe.

5.7.5.1 Spacing and Capacity of Sumps

Sumps must be located with a frequency, capacity, and configuration such that the leachate control system will drain by gravity to the sump when leachate is being produced at the maximum anticipated rate. Frequently, the locations of sumps are dictated by excavation requirements and collection system configurations. Hazardous waste landfill sumps should have a leachate storage volume equal to or greater than three months expected leachate production but not less than 1000 gallons. Assuming a porosity of 0.4 (fraction of gravel volume that is voids), the minimum volume of the sump that will be filled with rock must be at least 12 cubic yards.

The drain rock (1) must be free of fines that could reduce the transmissivity of the rock, (2) of a sufficiently coarse gradation so it does not enter the perforations or slots in the withdrawal pipe, (3) nonsoluble in an arid environment and (4) sufficiently protected from fines entering from adjacent soil and/or refuse. Satisfactory performance can be expected if the drain rock gradation and perforation/slotting width selected satisfies the following U. S. Bureau of Reclamation criterion (1973):

$$\frac{\text{D85 of the drain rock}}{\text{Perforation/slot width}} = 2$$

where D85 is the screen size through which 85% of the drain rock (by weight) could pass.

Figure V-2 in Appendix V can be used to determine the required sump capacity or withdrawal rates needed to ensure gravity flow from the leachate collection system under the maximum discharge rate. To determine the required capacity or withdrawal rate (1) locate on Figure V-1, also in Appendix V, the percolation rate that has been previously calculated by the water balance method, (2) rise vertically from the horizontal axis to the line corresponding to the average width of area tributary to the leachate collection pipe(s), and (3) move horizontally from the junction in (2) above to the vertical axis and read the flow per 1000 feet of collection pipe tributary to the sump.

5.7.5.2 Monitoring and Withdrawal

The riser pipe extending from the leachate sump must be of a diameter that will accommodate a pump suction line in shallow facilities or a submersible pump or air pump when the depth to the sump is greater than 20 to 25 feet. Due to the corrosive nature of leachates, inert pipe materials such as PVC or the equivalent should be used. The riser pipe can be installed in a trench excavated in the wall of the landfill or disposal trench excavation to protect the pipe from construction damage and stresses due to settlement of the fill. Alternatively, the riser can be installed vertically from the sump. To protect the riser pipe, it is advisable to install vertical risers within a larger diameter protective casing with the annular space filled with sand or fine gravel.

Typical construction details for leachate monitoring and withdrawal wells with vertical and inclined risers are shown on Figures 5-27 and 5-28 respectively.

5.6.6 Covers and Closure of Lined Waste Impoundments

Covers and closure are required for all lined waste impoundments. In addition to protecting the surrounding environment, covers should provide a pleasing aesthetic appearance. The subject of covers is presented and discussed in detail in the "Manual for Evaluating Cover for Hazardous Materials", a companion study to this document. The closure of a lined waste impoundment facility involves several components and procedures. This fairly complex operation is described in detail in another companion Manual, "Surface Impoundment Closure".

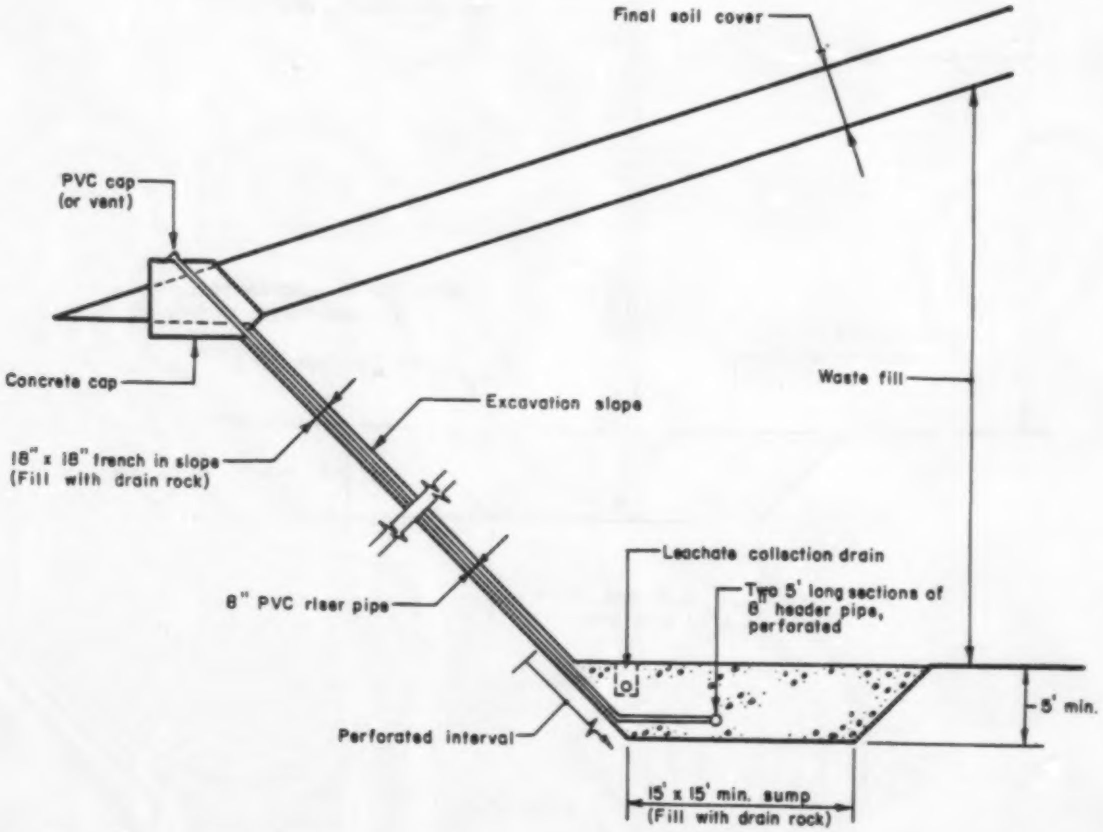

Final soil cover
PVC cap
(or vent)
Concrete cap
Excavation slope
Waste fill
18" x 18" trench in slope
(Fill with drain rock)
Leachate collection drain
Two 5' long sections of 8" header pipe, perforated
8" PVC riser pipe
5' min.
Perforated interval
15' x 15' min. sump
(Fill with drain rock)

Figure 5-27. Typical inclined leachate monitoring and removal system (Source: Emcon Associates).

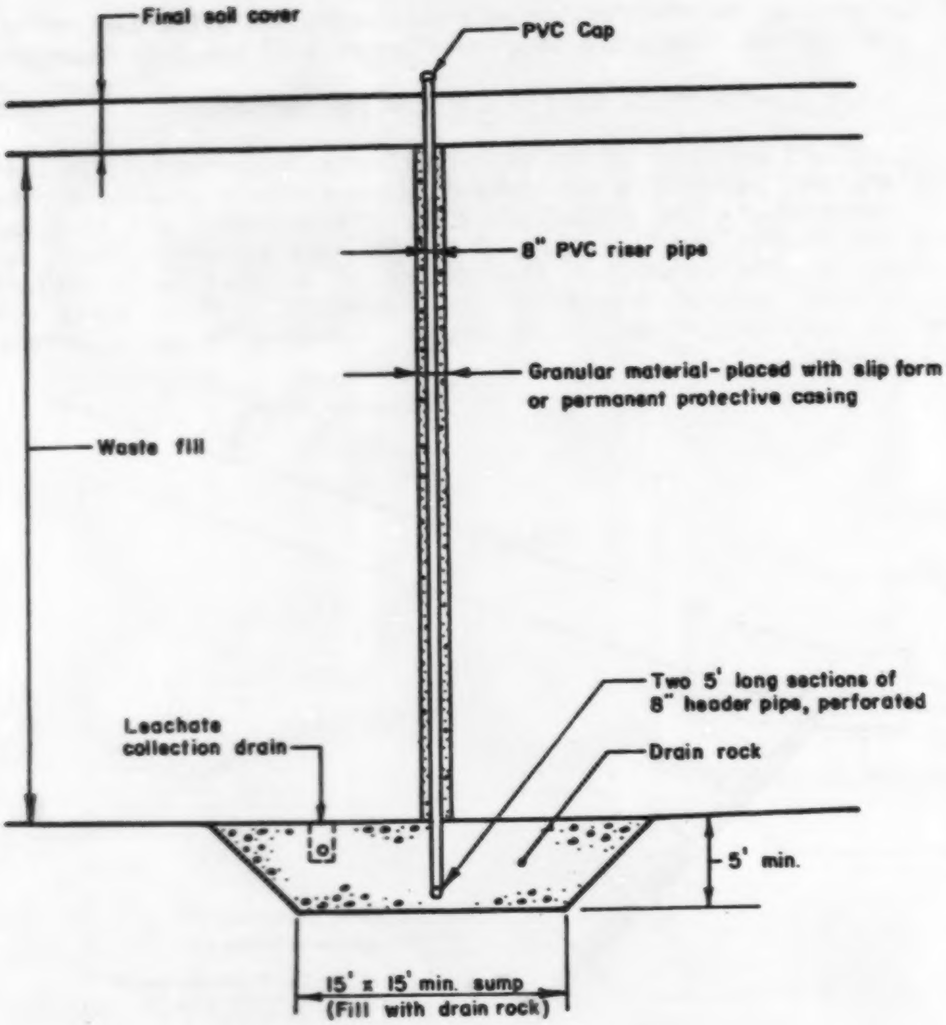

Final soil cover
PVC Cap
8" PVC riser pipe
Granular material- placed with slip form or permanent protective casing
Waste fill
Two 5' long sections of 8" header pipe, perforated
Leachate collection drain
Drain rock
5' min.
15' x 15' min. sump
(Fill with drain rock)

Figure 5-28. Typical vertical leachate monitoring and removal system (Source: Emcon Associates).

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CHAPTER 6. MANAGEMENT, OPERATIONS, AND MAINTENANCE OF LINED WASTE DISPOSAL FACILITIES

6.1 Introduction

The proper management of a lined waste disposal facility is important if the performance of the impoundment is to be maintained and the maximum life of the liner and the design criteria are to be realized. Special measures must be taken into account in the management of facilities that are lined. It is necessary:

a. To protect the integrity of the impoundment and of the liner.

b. To monitor the performance of the liner system to determine whether it is operating within the design criteria and is not failing, i.e. monitor the groundwater, the drainage system below the liner, piping, pumps, etc.

c. To monitor the condition of the liner to determine if there are any abnormal swelling, degradation, or changes in properties.

6.2 Standard Operating Procedures for the Impoundment

The two basic type of impoundments to be encountered are:

a. Pits, ponds, and lagoons.

b. Solid waste landfills.

The first group of impoundments are all open where the liner may or may not be exposed to the weather. Depending upon the materials and the construction, the liner may be protected by various types of covers. In the case of landfills, the liners will be buried for most of their service lives (see Chapter 5). Several standard handbooks and manuals are available on the operations of such impoundments. (EPA-OSW, 1978; ASCE, 1976; EPA, 1973) However, in the case of lined sites, additional information should be incorporated in the standard operating procedures for the specific disposal facility. The additional requirements and procedures in the Manual should reflect the specific type of material and construction that was used. The operations and procedures manual should be prepared by the design, construction, and operations team and should include, as a minimum, the following:

- Operation and maintenance staff requirements and structure.
- Facility description and design parameters.

- Emergency shut-down procedures.
- Operation variables and procedures.
- Facility trouble shooting procedures.
- Preventive maintenance requirements.
- Specialized maintenance procedures.
- Plant personnel safety requirements and procedures.
- Equipment maintenance records.
- Site inspection records
- List of permissible wastes.
- List of unacceptable wastes.
- Master file noting changes such as additions, revisions or deletions to procedures.

6.3 Information on the Design, Construction, and Materials of Construction

Detailed information regarding all of the components of the liner system should be available to the operating personnel. Of particular importance is information on the liner, and information on its characteristics and properties. This information should be obtained from the supplier, manufacturer of the liner, the designer of the site, and the installer. Quality control data and "as-built" drawings and information should also be obtained. Samples of the liner material and other components should be retained for possible use in cases of malfunctioning of the impoundment. A full discussion should be obtained from the supplier as to the limitations of the liner material. The material was selected on the basis of its compatibility with the wastes which it will contain; consequently, deviations in the waste composition from the anticipated composition should be avoided. Information of this type should be incorporated into the operating manual and into the operator training program.

6.4 Control of Incoming Waste

As indicated in the previous section, the composition and character of the waste must be controlled to avoid possible damage to the liner system. It is recognized that a control will be maintained of the hazardous materials that go into the impoundment. However, there is an additional requirement to avoid materials that might be aggressive to the liner. An approximate analysis should be performed on incoming waste to determine the amount of such constituents in the waste. Compatibility of the incoming waste with the wastes in the impoundment should be assured. Generally, there will be some dilution; however, the added waste may have a synergistic and damaging effect upon the liner. The operator should develop a knowledge of the types of industries in the area to be aware of those materials that might be encountered as wastes for the disposal.

Liquids or sludges to be placed in a landfill should be chemically fixed, mixed with MSW, soil or a suitable dry absorbent so that the resulting mixture is not free flowing. Drums and other containers of hazardous wastes should be surrounded by an inert absorbing material to prevent migration of leaked waste which might damage or penetrate a liner.

In order to know the contents of the waste impoundment, records should be kept of the wastes being disposed. This, of course, is being done to meet the standard requirements; however, the organic and inorganic constituents that are aggressive toward liners should also be recorded. The waste should be analyzed periodically in order to know its composition. Chemical reactions and volatilization of the constituents within the waste impoundment will probably change the composition of the waste. Adequate means should be incorporated in the design of the impoundment for the additon of wastes. Over-the-edge dumping of wastes should be avoided, as should the additon of hot waste directly on a liner. Various sacrificial covers have been used.

6.5 Monitoring the Performance of the Impoundment

The principal purpose of the impoundment is to contain a waste and prevent pollutants from leaving the impoundment. Consequently, the principal means of measuring the performance of such an impoundment is to monitor either a drainage system below the liner or the groundwater. These techniques are described in EPA-OSW (1977). In addition, the leachate collection system, if leachate is being collected above the liner, should be inspected for the output and composition of the leachate. It is recognized that considerable time may elapse before the generation of leachate.

If a diversion drainage system is set up around the impoundment, this should be inspected periodically to insure that drainage is being diverted.

6.6 Monitoring the Liner

A system of monitoring the liner should be devised and, if necessary, incorporated in the design of the liner system to observe the condition of the liner itself. The use of coupons at the bottom of a fill or other impoundment has been discussed in Chapter 5. A program of retrieval of these coupons should be set up to cover the operating time of the impoundment before it is closed.

Any damage to a liner that is observed should be repaired as quickly as possible in order to avoid a massive failure. Openings in the liner can cause damage to the earthwork below. The vents should be inspected regularly to avoid plugging.

Impoundments holding wastewater may require cleaning to remove sludges. Care must be taken during cleaning so as not to damage the liner. Cleaning crews should be supervised by someone familiar with the liner to assure that punctures or tears are prevented, or patched if they occur. If sludge is to be removed from the bottom of a wastewater impoundment, some type of non-mechanical means should be used, e.g. a suction hose or dredging head. This should minimize the potential for liner damage.

Following cleaning, the liner should be thoroughly inspected for its condition and possible distress.

6.7 Condition of Earthwork

In the case of ponds and lagoons, regular inspections should be made of the embankments and berms. Attention should be given to possible ground movements, cracks, and erosions of the earth. Since an erosion control problem usually exists when earth is exposed on an embankment slope, preventive measures should be taken in the design. However, the inspection is still needed because failure of the earthwork can result in failure of the liner.

6.7.1 Vegetation Control

Growth of vegetation must be controlled around the perimeter of any impoundment. This must be accomplished to prevent damage to the liner from the anchor trench down the side slope. Damage can result if weed growth begins under the liner or, if a soil cover is present, on top of the liner. In the latter case, roots of plants can penetrate the liner creating a potential failure point. Ideally, the berm area around the impoundment should be treated with weed killer initially, and maintained in a weed-free condition.

6.7.2 Rodent Control

Rodents, such as gophers, squirrels, rats, muskrats, and mice, can present severe problems for the owner of a lined impoundment. These animals will attack and possibly damage a liner if the liner blocks their path to food or water. Rodents have also been known to eat PVC material, particularly certain ground squirrels. The presence of these animals at the construction site should be assessed during design. Provisions to control their impact can then be made and incorporated into construction.

6.8 Inspection of Appurtenances

Many of the failures of liner systems occur at penetrations of the liner by appurtenances. Whenever possible, these should be inspected on a regular basis to check their integrity and make the needed repairs.

6.9 General Comments

It is desirable to make on-site inspection of the impoundment on a regular basis and to perform preventive maintenance.

Vandalism and unauthorized dumping of wastes must be carefully monitored. These may be curtailed by having limited vehicular access to the disposal site, locating the site out of general view, and by fencing in ponds and similar impoundments.

Inasmuch as liner technology is relatively new and basic experience is limited, good records should be kept of the performance of the sites. Failures and difficulties should be noted.

6.10 Unacceptable Practices

Certain operational procedures are not acceptable if the integrity of the lined waste impoundment facility is to be maintained. These procedures include, but are not limited to, the following:

a. The discharge of high-temperature waste liquids onto exposed or unprotected liners, i.e. liners with no soil cover or with insufficient standing liquid levels.

b. The passage of any vehicle over any portion of an exposed liner.

c. The discharge of incompatible wastes to the facility.

d. The direct discharge of wastes with high hydraulic energy upon a liner without adequate provision for energy dissipation.

e. Unauthorized modifications or repairs to the facility.

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CHAPTER 7. LINER COSTS FOR LINED WASTE DISPOSAL FACILITIES

7.1 Introduction

Costs may be an important factor in the ultimate choice of liner material for a given site. In order to conduct an adequate cost analysis, the preliminary design criteria for facilities should be set forth. The cost of the liner is but part of the total cost of the construction of a lined disposal facility. A number of additional cost items that are affected by the type of liner material, e.g. subgrade preparation, are discussed in the following section.

7.2 Capital Cost

The parameters described and discussed in Chapter 3 and Chapter 5 provide the technical basis for planning, design, construction, and management of waste impoundment and disposal facilities. Table 7-1 is a listing of the significant cost parameters. It is important to note that the parameters of interest extend from just below the waste impoundment cover to just below the subgrade.

A short discussion of each item is provided in the following paragraphs. For those individuals involved in the planning and permitting process, particular attention should be paid to the variability of each parameter. For example, the costs of many of the parameters are site specific, such as rough grading and groundwater monitoring systems.

The cost of materials delivered to the site includes all costs of all materials not contained within the site itself. Liner costs are presented in Tables 7-2 and 7-3. Most of the cost data are for 1976 or earlier. Only limited current data are in the tables; however, they show the large increases that have occurred during the past several years. The ratios of the costs shown for 1976 are believed to be satisfactory.

Prior to rough grading, the site should be cleared of all tall grasses, trees, brush, fences, poles, stubs, rubbish, debris and refuse. Excavation methods are determined by the scope of the project and the results of the soils investigation. Obviously, economies of scale can be achieved for larger projects. Costs should be determined on a component basis, i.e. the cost of a dozer or front end loader or other moving machinery. For membrane liners, the surface should be smooth, and free from any fractured rock, and no smooth rock should be over 1/4" in diameter. If a sand bedding is placed over the excavated surface, the proof-rolling requirement would be the same. If a geotextile underlay is to be installed the same proof-rolling requirements applies, and a surface deviation should be less than 0.1 foot across a 10 foot section. This will be accomplished generally by smooth wheeled or pneumatic tire rollers.

TABLE 7-1. CAPITAL COST ITEMS RELEVANT TO LINED WASTE IMPOUNDMENT AND DISPOSAL FACILITIES

Cost of materials delivered to the site

Site preparation:

- Rough grading
- Subgrade preparation
- Compaction
- Surface smoothing

Costs associated with installation of liner(s):

- Special structures adaptation
- Anchoring
- Field seaming
- Quality control testing

Groundwater monitoring systems, if necessary, only at lining Interface

Soil cover costs

Liner cover costs

Leachate control system, only at interface with lining(s)

Gas control system, only at interface with lining(s)

Fill for the soil liner should be placed in lifts not exceeding the thickness recommended by the geotechnical engineer. Each lift should be compacted to the recommended percentage of the maximum dry density as determined by the Standard of Modified Proctor Moisture-Density Relationship. Embankments should be slightly overfilled and then cut to finish grade. All tolerances which applied to excavated surfaces also apply to fill. The cost of imported fill and its placement can contribute substantially to the cost of the project.

Proof-rolling of subgrades, usually required for membrane liners, is done with a heavily loaded rubber-tired roller. A soft subgrade condition should be overexcavated, material removed, and replaced with suitable fill compacted to required density. This is the final cost of subgrade preparation.

It is important to establish a quality control plan for compaction and moisture control. This serves two important functions. A uniform density is attained which assures both owner and engineer that the project is constructed as designed, and it provides the data for cost control when field densities are higher than required; this eliminates unecessary earthwork. The quality control program specifies the test frequency to ensure accurate and reliable

TABLE 7-2. COSTS OF FLEXIBLE POLYMERIC MEMBRANE, PLASTIC, AND RUBBER LINERS

Material	Nominal thickness mils	Fabric reinforcement[a]	1973 Price, fob $\$/yd^2$	1973 Installed cost[c] $\$/yd^2$	1977 Delivered cost[b] $\$/yd^2$	1977 Installed cost[c] $\$/yd^2$	1980 Installed cost[c] $\$/yd^2$
Butyl rubber	30	no	2.25	3.25-4.00	2.70-3.15	3.40-3.60	
		yes	...	...	2.79-3.24	...	...
Chlorinated polyethylene (CPE)	30	no	2.25	2.43-3.24	2.70-3.15	3.10-3.50	6.17[d, e]
		yes	...	...	2.79-3.24	3.24-3.78	...
Chlorosulfonated polyethylene (CSPE)	30	no			2.70-3.15	3.10-3.50	...
		yes	1.66	2.88-3.06	2.79-3.24	3.24-3.78	7.50-8.50[f, g]
Elasticized polyolefin (ELPO)	20	no	...	...	1.80	2.07-2.25	...
Ethylene propylene rubber (EPDM)							
covered	30	yes	2.00[h]	2.43-3.42	2.70	3.42-3.50	...
uncovered	30	yes	...	...	2.16	2.88	...
Neoprene (CR)	30	no	2.07	4.41-5.40	...	...	...
		yes	...	...	5.00	5.85-6.75	...
Polyethylene (PE)	10	no	0.36	0.90-1.44	0.60-0.70	1.10-1.40[i]	...
Polyvinyl chloride (PVC)	20	no	.90	1.17-2.16	1.11-1.53	1.44-1.98	...
	30	no	1.33	...	1.44-1.89	1.80-2.45	...

[a] Fabric reinforcement, usually nylon or polyester scrim.

[b] Delivered cost in dollars per square yard; cost of sheeting in panel - 5000 to 150,000 sq. ft.

[c] Installed cost is highly dependent on area being lined.

[d] 45 mil thickness, three ply, one ply polyester scrim.

[e] Engineering News Record, July 10, 1980, p. 61, does not include subgrade preparation of soil cover.

[f] 45 mil thickness, five ply, two ply polyester scrim.

[g] Winning bid, June 11, 1980, City of Seattle, North Beacon Reservoir Reline.

[h] The cost over the range of area of 150,000-500,000 sq ft is usually in the range of \$0.05-0.06 per square foot.

Soil cover: 1) $\$.10-.50/yd^2$/foot of depth
2) $.05-.07/ft^2$/foot of depth

[i] If tape is used, tape cost: \$0.05-.06/linear foot

TABLE 7-3. COST ESTIMATES OF SOIL, ADMIX MATERIALS AND ASPHALT MEMBRANE LINERS

Liner type	Installed Cost Dollars per square yard 1973	 1980
Soil + bentonite 9 lb/sq yd (1 psf)	$0.72	-
Soil cement 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	-
Soil asphalt 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	-
Asphalt concrete, dense -graded paving with sealer coat (hot mix, 4-in thick)	2.35 - 3.25	5.00 - 7.00
Asphalt concrete, hydraulic (hot mix, 4 in thick)	3.00 - 4.20	-
Bituminous seal (catalytically blown asphalt) 1 gal/sq yd	1.50 - 2.00 (with earth cover)	-
Asphalt emulsion on mat (polypropylene mat sprayed with asphalt emulsion)	1.26 - 127	-

[a] Haxo, 1976 (October,1973 costs).
[b] Estimated installed costs on west coast.

field density data and is tailored to the specific needs and requirements of the project.

Surface smoothing, the thorough preparation of the finished surface, is a major ingredient in the success of a lined system. In general the surface must provide a firm, unyielding and smooth foundation, free of debris of any kind. The surface should be graded smooth and compacted to finished elevations in accordance with the recommended tolerances.

As discussed previously, it is very important to remove roots and root contaminated topsoil. The prepared subgrade should be treated with a reliable herbicide for this purpose. This subgrade sterilant should be applied in a uniform manner over the entire site. The cost of application is included with the cost of the herbicide for the total cost of subgrade sterilization.

The costs for construction/installation of liners is principally associated with skilled labor. Depending upon the type of liner selected, equipment rental may be significant. The major cost components are those costs associated with special structures adaptation (penetrations such as inlet structures, concrete piers or pads, sumps, etc.), anchoring of membrane liners, field seaming of membrane liners, and quality control testing. The preceding are affected by weather conditions at the time the tasks are accomplished and the degree of complexity of each item. As with site preparation, certain economies of scale can be achieved with large projects.

7.3 Annual Cost Items

In addition to the capital costs, there are annual costs of operating and maintaining a lined disposal facility. The liner type may influence some of these costs. The annual cost items relating to liner waste impoundments are listed below:

- Debt service or amortization
- Periodic field checks (surveys) - lining(s), control systems, monitoring system(s)
- Periodic maintenance
- Operation costs

7.4. Case Study Methodology for Analyzing Cost

To facility a deeper understanding, the "case study" analysis methodology has been selected as the vehicle for estimating costs of lined disposal facilities and to aid in liner selection. In case study analysis, detailed construction drawings and specifications are neither prepared nor desired. Instead, it is necessary only that a reasonably close approximation of the size, location, type of construction, general layout and costs of various components be developed and that this information be given in sufficient detail to permit comparisons between alternative plans or with established standards. Such a case study is presented in Appendix VII.

CHAPTER 8. SELECTION OF A LINER MATERIAL FOR A WASTE DISPOSAL FACILITY

8.1 Introduction

The designer of a lined waste disposal facility is faced with making the selection of a liner or liners which meet a wide range of requirements. This Chapter summarizes the approach that could be taken making that selection.

It is assumed that a basic decision has been made as to the site for the waste disposal facility; however, there are factors in the soil and geology of the site which must be known before the site selection can be made. Obviously, the soil and geology at one site would be preferable to another from the standpoint of impoundment requirements. In making a decision regarding the selection, it is necessary to consider the liner as a part of a many-layered system of different permeabilities and characteristics. These layers extend from the waste itself and the waste fluid through the liner and subgrade, the soil base and finally the aquifer. The principal factors can be enumerated as follows:

- Type of waste and composition.
- Required operating life of disposal facility.
- Required life of the liner after closure of the facility.
- Soils on or nearby site, including subsoil.
- Hydrology and groundwater.
- Significant environmental factors.
- Acceptable flow out of impoundment.
- Permeability of soil liner.
- Review of available materials which appear to be potentially compatible.
- Compatibility tests of specific materials with sample of the waste to be contained.
- Costs of principal candidate material and installation.
- Reliability of materials, seams, joints, etc. and documented experience in the technology.

8.2 The Function of the Waste Disposal Facility

The first thing that must be known is the type of waste that is to be contained, whether it be a solid, liquid, sludge, etc. The type of waste will determine the general type of disposal site. solid waste generally will go into landfills, and liquid or partially liquid waste will be impounded in ponds or lagoons. The character of the waste itself should be known as to its chemical composition and whether there are components present that are highly aggressive to the various types of lining materials.

The designer should know the anticipated life required of the impoundment. A landfill liner should last for extended periods of time. Many impoundments are either evaporating or holding ponds which may require only relatively short periods of service. The selection of a liner can be greatly affected by the anticipated required service life.

Superimposed on these factors is the basic performance requirement that will be imposed by the various regulatory agencies. Together, these will form a minimum performance requirement for the site.

8.3 Soils on Site

It is important to know whether the soil on site is available from a borrow pit nearby, whether it can be used as a liner, with or without compaction, or whether it should be used as a subgrade for other types of lining materials. From the cost standpoint, soils are generally the least expensive, but they have a variety of limitations.

In making the decision as to the suitability for the liner, the permeability to water and to the waste fluid should be determined. Further tests as to the sensitivity of the soil, such as described in Chapter 4, including testing of the plastic and liquid limits with water and with waste fluids should be conducted.

Tests should be made as to the structural strength of the soil. If the soil does not have adequate permeability or is sensitive to the waste, it still must be tested to determine its quality as a subgrade, where strength is a major factor.

8.4 Hydrology

The groundwater level is an important factor in the siting of a waste disposal facility, but it also should be evaluated and determined as a part of the liner selection process as should the permeability of the soil below the facility. The permeability of the native soil and its thickness can have a significant bearing on the design of the soil liner, as discussed in Chapter 5 and Appendix VII. The flow of water within the aquifer also can be a factor in the total system as there can be a dilution of any pollutant species that might enter the aquifer.

8.5 Significant Environmental Factors

The significant environmental factors include such items as prevailing winds, temperature, rainfall, drainage, and the subsurface geology. It is important to know the overall geological character of the rocks, soil, depth of strata, and the chemical and physical characteristics of the subgrade soils, clays, and rocks.

8.6 Acceptable Flow Through a Liner

Once the permeabilities have been obtained for the various layers that make up the impoundment system from waste to groundwater, one can calculate the thickness of a liner of a given permeability to meet the basic flow requirements. It is possible, in making this calculation, that the specific soils which were expected to be used will require too great a thickness to be compacted properly. At this point, the decision may be that other lining materials must be used.

8.7 Review of Available Materials

At this point, with the knowledge of the waste that will be impounded and the level of permeability required in the liner, review should be made of those materials which appear potentially suitable as liners. A screening of these materials can be made based upon the state-of-the-art knowledge and a selection made of those which are potentially compatible with the waste fluid. Information in this Manual and some of the references should be useful. Also, guidance can be obtained from suppliers of lining materials.

8.8 Cost of Liner Materials

A preliminary estimate can be made of the costs of the various lining materials such as found in Chapter 7. It is anticipated that several lining materials may be suitable for the lining of the specific site and the selection can be based upon costs and other considerations.

8.9 Compatibility Tests

The principal candidates for the liner should be subjected to some tests in direct contact with the waste. Compatibility tests for soils and membranes have been suggested in Appendix III. These tests should indicate the compatibility of the liner to long exposure with the wastes. Incompatible combinations should become obvious. It is recognized, however, at this state-of-the-art, that extended lives of many years have not been demonstrated in actual service; at this point, dependence must be placed on accelerated testing to assess compatiblity and durability.

8.10 Selection of Liner Material

In making the final selection of a liner material, some factors take precedence over others. The principal function of the liner is to impede the flow of pollutants from the impoundment for the duration of its required life and sometimes to form the table on which the flow of a leachate can take place for collection and treatment.

Although there may be some variation in the priority of the factors, the following requirements must be met:

a. Compatibility and durability of the liner in the presence of the fluid to be contained.

b. Low permeability to the waste over extended periods of time.

c. Reliability and low risk of failure.

d. Relative ease of installation, quality control, repair, and maintenance.

The selection can also depend on cost if the above requirements are all met. Following the liner selection, the designer can proceed with the detailed design of the disposal facility as it relates to the liner. It is recognized that more than one material may be selected in which case some alternatives may have to be incorporated in the drawings and specifications.

CHAPTER 9. SPECIFICATION FOR CONSTRUCTION OF LINED WASTE IMPOUNDMENTS

9.1 Introduction

After selecting the liner material and incorporating it into the design of the waste disposal facility, the architect-designer-engineer must prepare the necessary specifications and drawings for the bid package and for use in construction of the facility.

As in all engineering projects, the preparation of good specifications is essential to obtaining satisfactory construction or to meeting the goals of the project (Goldbloom and White, 1976). Incomplete drawings and specifications can result in high-price bids, construction uncertainties, and inadequate product and performance. It is not possible to prepare adequate performance specifications on a product such as a waste impoundment. Too many uncertainties exist with respect to the performance of different materials and long periods of time are required to demonstrate effective performance. As a consequence, the specifications must be requirements based upon procedures, as well as performance.

9.2 Specifications for Construction

In view of the complexity and long times that are required to demonstrate the performance of a lined waste disposal facility, it is necessary to prepare detailed specifications for the construction of the facility. Following these procedures should increase the probability of meeting the project requirements and assuring an effective waste disposal facility. These specifications should include specific instructions for the following:

- Site preparation, embankment, and other earthwork.
- Subgrade preparation.
- Liner construction for soils, admixes, sprayed-on materials
- Liner installation, particularly field seaming.
- Quality control - quality assurance.
- Drainage and gas venting systems.
- Appurtenances and penetrations.

Construction details are presented in Chapter 5. Table 9-1 lists references which give examples of detailed procedures of the construction, various types of liners, and includes subgrade earthwork and subgrade preparation.

TABLE 9-1. CONSTRUCTION PROCEDURES AND SPECIFICATION FOR LINERS OF WASTE DISPOSAL FACILITIES

Preliminary[a] List of Suggested References

Liner type	References	
	Liner	Subgrade and earthwork
Clayey soil	Bureau of Reclamation, 1964, p. 189 Bureau of Reclamation, 1977, pp. 669-700	Day, 1970, pp.46-47 Bureau of Reclamation, 1964, pp.176-184
Admix - Asphalt concrete	Day, 1970, pp. 52-60 Asphalt Inst., 1976, pp. 13-18 Asphalt Inst., 1975, 60 pp.	Day, 1970, pp. 46-47 Asphalt Inst., 1976, pp. 8-9
Soil cement	Day, 1970, pp. 60-64 PCA, 1979	Day, 1970, pp. 46-47
Bentonite soil	Day, 1970, pp. 64-66 American Colloid Co. and Dowell Trade Literature	Day, 1970, pp. 46-47 American Colloid Co. and Dowell Trade Literature
Soil asphalt	Day, 1970, pp. 64-66	Day, 1970, pp. 46-47
Flexible membrane	Water and Power, pp. 4-1 - 4-9 Day,1970, pp. 47-50 Appendix IX Small, 1980 Manufacturers and Suppliers Trade Literature	Water and Power, pp. 3-4 - 3-6 Day, 1970, pp. 46-47 Small, 1980 Manufacturers and Suppliers Trade Literature
Spray-on - Membrane Asphalt Modified asphalt	Asphalt Inst., 1976, pp. 19-20 Day, 1970, pp. 50-51 Chevron USA, 1978, pp. 7-9, 13-15 Chevron USA, 1980, pp. 1-9	

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[a] To be expanded in revisions.

9.3 Materials Specifications

In addition to the construction specifications, the liner materials must be controlled and tightly specified. The properties of the various lining materials are described in Chapter 3 and their installation is described in Chapter 5.

The range of materials that fall under this category of polymeric materials, as indicated in Chapter 3 is extensive and the technology is relatively new. Specifications have been developed by polymer manufacturers, sheeting and film manufacturers, and panel fabricators. The specifications thus have come out of the rubber, plastics and textile techologies and have varied considerably in requirements and in test methods. Even though several test methods may be used to assess the same property, e.g. tear strength, the specimens, rates of test, temperatures, etc. have varied. Several organizations setting standards have prepared specifications on polymeric lining materials such as:

American Society of Agricultural Engineers	(ASAE)
American Society of Civil Engineers	(ASCE)
American Society for Testing and Materials	(ASTM)
American Water Works Association	(AWWA)
National Sanitation Foundation	(NSF)
U.S. Bureau of Reclamation	

Recently the National Sanitation Foundation and the liner industry have undertaken to prepare general standards. All segments of the industry, including raw materials producers, membrane manufacturers, fabricators, installers, and design engineers are participating by developing concensus standards. The current drafts of the standards are presented in Appendix IX. When specifying flexible membrane liners, the tables may provide useful information but should be used with discretion. The values are preliminary and subject to change.

These specification tables represent current opinion of the data points to characterize the membrane product as now on the market and are not proper for product performance or installation or engineering design criteria per se. For example, the low temperature resistance numbers represent qualities for a few minutes at a given temperature and must not be interpreted or extrapolated into installation temperature qualities or comparisons.

These specifications should not be used to select materials; selection, as indicated in Chapter 8, should be based upon factors of compatibility, durability,etc. These specifications should be used as a means of assuring the quality of the product that will be placed in the waste disposal facility.

Liner technology is progressing. The industry is developing new materials and new products are being introduced. The designer and engineer will incorporate these in their designs for lined disposal facilities.

REFERENCES

Chapter 9 - Specification for Construction of Lined Waste Impoundments

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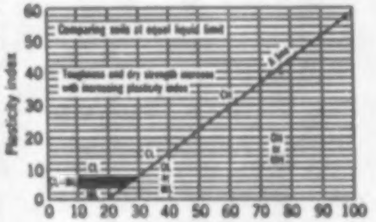
APPENDIX I

UNIFIED SOIL CLASSIFICATION

Field Identification Procedures (Excluding particles larger than 75mm and basing fractions on estimated weights)							Group Symbols ^{a}	Typical Names	Information Required for Describing Soils	Laboratory Classification Criteria		
Coarse-grained soils More than half of material is larger than 75 μm sieve size ^{b} (The 75 μm sieve size is about the smallest particle visible to naked eye)	Gravels More than half of coarse fraction is larger than 4.75mm sieve size	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes				GW	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbols in parentheses For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics Example: *Silty sand, gravelly*; about 20% hard, angular gravel particles 12 mm maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (*SM*)	Use grain size curve in identifying the fractions as given under field identification Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than 75 μm sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP* More than 12% *GM, GC, SM, SC* 5% to 12% *Borderline* cases requiring use of dual symbols	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing				GP	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*	
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)				GM	Silty gravels, poorly graded gravel-sand-silt mixtures			Atterberg limits below "A" line, or *PI* less than 4	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)				GC	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7	
	Sands More than half of coarse fraction is smaller than 4.75mm sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes				SW	Well graded sands, gravelly sands, little or no fines			$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing				SP	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*	
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)				SM	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)				SC	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7	
Fine-grained soils More than half of material is smaller than 75 μm sieve size			Identification Procedures on Fraction Smaller than 380 μm Sieve Size									
				Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)						
	Silts and clays liquid limit less than 50			None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions Example: *Clayey silt*, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)		 Liquid limit Plasticity chart for laboratory classification of fine grained soils	
				Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays				
				Slight to medium	Slow	Slight	OL	Organic silts and organic silt-clays of low plasticity				
	Silts and clays liquid limit greater than 50			Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts				
				High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays				
				Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity				
Highly Organic Soils			Readily identified by colour, odour, spongy feel and frequently by fibrous texture				Pt	Peat and other highly organic soils				

From Wagner, 1957.

^{a} *Boundary classifications.* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW–GC*, well graded gravel-sand mixture with clay binder.

^{b} All sieve sizes on this chart are U.S. standard.

Field Identification Procedures for Fine Grained Soils or Fractions

These procedures are to be performed on the minus 380 μm sieve size particles. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (Reaction to shaking):

After removing particles larger than 380 μm sieve size, prepare a pat of moist soil with a volume of about 8000 mm³. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (Crushing characteristics):

After removing particles larger than 380 μm sieve size, mould a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun or air drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (Consistency near plastic limit):

After removing particles larger than the 380 μm sieve size, a specimen of soil about 12 mm cube in size, is moulded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about 3 mm in diameter. The thread is then folded and re-rolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

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APPENDIX II

REPRESENTATIVE LIST OF ORGANIZATIONS IN LINER INDUSTRY

A. POLYMERIC MEMBRANE LINERS

  1. Polymer producers
  2. Manufacturers of polymeric membrane sheeting
  3. Fabricators of liners
  4. Installing contractors

B. BENTONITE PRODUCERS AND SUPPLIERS

C. OTHER LINER MATERIALS

D. MISCELLANEOUS ORGANIZATIONS IN THE LINER INDUSTRY

A. POLYMERIC MEMBRANE LINERS

1. Polymer Producers

DOW CHEMICAL COMPANY
2040 Dow Center
P.O. Box 1847
Midland, MI 48640

Product Sales Manager,
Chlorinated Polyethylene Designed Products Department
Phone: 517-636-1000

E.I. du PONT de NEMOURS AND CO., INC.
Elastomer Chemicals Dept.
Wilmington, DE 19898

Contact: Bernard F. Anderson
Phone: 302-774-1000
Contact: Gerald E. Fisher
3707 Chevy Chase Road
Louisville, KY 40218
Phone: 502-459-8752

EXXON CHEMICAL CO.
Elastomer Technology Division
P.O. Box 45
Linden, NJ 07036

Contact:
Phone: 201-474-0100

HERCULES INCORPORATED
910 Market St.
Wilmington, DE 19899

Contact: Norman C. MacArthur
Phone: 302-575-6293

MONSANTO INDUSTRIAL CHEMICALS CO.
260 Springside Drive
Akron, OH 44313

Contact: Gary E. O'Connor,
Project Manager
Commercial Development Department
Rubber Chemicals Division
Phone: 216-666-4111

PANTASOTE, INC.
26 Jefferson St.
Passaic, NJ 07055

Contact: Dr. R. Brookman
Phone: 201-777-8500

POLYSAR, LTD.
Technical Development Division
Vidal Street
Sarnia, Ontario
Canada N7T 7M2

Contact: John Redland
Phone: 519-337-8251

SHELL CHEMICAL COMPANY
605 N. Main Street
Altamont, IL 62411

Contact: Larry Watkins
Phone: 618-483-6517

UNIROYAL CHEMICAL COMPANY
Spencer Street
Naugatuck, CT 06488

Contact: Allen Crepeau
Phone: 203-723-3825

2. Manufacturers of Polymeric Membrane Sheetings

BURKE RUBBER COMPANY
2250 South Tenth St.
San Jose, CA 95112
Contact: D. Kutnewsky
Manager, Flexible Membranes
Phone: 408-297-3300

CARLISLE TIRE AND RUBBER CO.
Construction Materials Department
P.O. Box 99
Carlisle, PA 17013
Contact: Hugh Kenney
Phone: 717-249-1000

COLUMBUS COATED FABRICS
1280 N. Grant St.
Columbus, OH 43216
Contact: Lee Fishbein
Phone: 614-225-6069

COOLEY, INC.
50 Esten Ave.
Pawtucket, RI 02862
Contact: Paul Eagleston
Vice President
Phone: 401-724-9000

DUNLINE LIMITED
(A Dunlop Company)
160 Eglinton Ave. E.
Toronto, Ontario
Canada M4P 1G3
Contact:
Phone: 416-487-1114

GACO
P.O. Box 88698
Seattle, WA 98188
Contact: Earle Johnson
San Jose, CA
Phone: 415-341-5661

B. F. GOODRICH COMPANY
Engineered Rubber Products Division
500 S. Main Street
Akron, OH 44318
Contact: R. D. Cunningham,
Sales Manager,
Environmental Products
Phone: 216-379-2226

GUNDLE PLASTICS, INC.
5340 Alpha Road Suite 101
Dallas, TX 57520
Contact: Richard K. Schmidt
Phone:

HART & COMPANY
16 E 34th St.
New York, NY 10016
Contact: R. H. Dickinson
Phone: 212-481-1210

KOKOKHU, USA, INC.
P.O. Box 2287
Everret, WA 98203
Contact: Ms. Miki Nakamura
Phone: 806-353-7000

MAINLINE, INC.
3292 South Highway 97
Redmond, OR 97756

Contact: DeWitt Maine
Phone: 503-548-4207

PANTASOTE, INC.
26 Jefferson St.
Passaic, NJ 07055

Contact: Dr. R. Brookman
201-777-8500

PLYMOUTH RUBBER COMPANY
104 Revere Street
Canton, MA 02021

Contact: Charles Neese
Phone: 617-828-0220

REEVES BROS., INC.
Vulcan Coated Fabrics Division
P.O. Box 431
Rutherford, NC 28139

Contact: Walter McEvilly,
Vice President,
Sales and Marketing
Phone: 704-286-9101

SCHLEGEL LINING TECHNOLOGY, INC.
P.O. Box 7730
The Woodlands, TX 77380

Contact: James M. Price, President
Phone: 713-273-3066 (Conroe)
713-350-1813 (Houston)

SEAMAN CORP.
P.O. Box 11007
Charlotte, NC 28209

Contact: Jack Watson
Phone:

SHELTER-RITE, INC.
P.O. Box 331
Millersburg, OH 44654

Contact: Dr. Bala Venkataraman,
Vice President,
Research and Development
Phone: 216-674-2015

STAUFFER CHEMICAL CO.
4407 S. Broad St.
Yardville, NJ 08620

Contact: William F. Christie,
Technical Manager
Phone: 201-549-6880

STEVENS ELASTOMERIC & PLASTICS
PRODUCTS, INC.
27 Payson Ave.
Easthampton, MA 01073

Contact: Arnold G. Peterson
Phone: 413-527-0700

TENNECO CHEMICALS, INC.
P.O. Box 189
Piscataway, NJ 08805

Contact: Bob Hayes/Kent Turner
Phone: 201-356-2550

UNIROYAL, INC.
312 N. Hill St.
Mishawaka, IN 46544

Contact: D. L. Zimmerman
Phone: 219-256-8181

3. Fabricators of Liners

BROWN AND BROWN
P.O. Drawer 269
Mobile, AL 36601

Contact: Sam Brown, President
Phone: 205-479-6581

ELECTRA TARP, INC.
Park Centre
7241 Whipple Ave., N.W.
North Canton, OH 44720

Contact: Bob Fulmer, President
Phone: 216-497-1496

ENVIRONETICS, INC.
9824 Industrial Drive
Bridgeview, IL 60455

Contact: Ray Winters, President
Phone: 312-585-6000

FABRICO MANUFACTURING CORP.
1300 West Exchange Avenue
Chicago, IL 60609

Contact: Jay Sabath, Sales Manager
Phone: 312-254-4211

MCKITTRICK MUD CO.
P.O. Box 3343
Bakersfield, CA 93305

Contact: Bill Wheeler, President
Phone: 805-325-5013

PALCO LININGS, INC.
7571 Santa Rita Circle
P.O. Box 919
Stanton, CA 90680

Contact: Richard Cain,
Senior Vice President
Phone: 714-898-0867

POLY-PLASTICS
P.O. Box 299
Springfield, OH 45501

Contact: Roland Harmer, President
Phone: 513-323-4625

PROTECTIVE COATING, INC.
1602 Birchwood Ave.
Ft. Wayne, IN 46803

Contact: Elmo Murrell, President
Phone: 219-422-7503

M. PUTTERMAN & CO.
2221 West 43rd Street
Chicago, IL 60609

Contact: A. Berman, President
312-927-4120 -

REVERE PLASTICS
16 Industrial Avenue
Little Ferry, NJ 07643

Contact: Larry Smith, President
Phone: 201-641-0777

SOUTHWEST CANVAS MFG. CO.
Oklahoma City, OK

Contact: Richard C. Nelson,
Manager
Phone: (405) 672-3355

STAFF INDUSTRIES
240 Chene Street
Detroit, MI 48207

Contact: Charles E. Staff,
President
Phone: (313) 259-1820
(800) 526-1368

SYNFLEX INDUSTRIES, INC.
2004-750 Jervis Street
Vancouver, British Columbia
Canada V6E 2A9

Contact: Gerald W. Salberg,
President
Phone: (604) 682-3621

WATERSAVER COMPANY, INC
P. O. Box 16465
Denver, CO 80216

Contact: Bill Slifer,
Vice President
Phone: 303-623-4111

MANUFACTURERS WHO ALSO FABRICATE

Burke Rubber Company
Carlisle Tire and Rubber Co.
B. F. Goodrich
Schlegel Area Sealing Systems, Inc.

4. Installing Contractors

CRESTLINE SUPPLY CORP.
2987 South and 300 West
Salt Lake City, UT 84115

Contact: Guy Woodward
Phone: 801-487-2233

ENVIROCLEAR, INC.
P.O. Box 242
Falls Village, CT 06031

Contact: Don Thompson, President
Phone: 212-997-0100
518-325-3332

AL GASTON CONSTRUCTION CO., INC
Gaston Containment Systems
P.O. Box 1157
El Dorado, KS 67042

Contact: John Saens
Phone: 316-321-5140

GLOBE LININGS, INC.
1901 East Wardlow Road
Long Beach, CA 90807

Contact: William Kays
Phone: 213-426-2587
213-636-6315

GULF SEAL CORPORATION
601 Jefferson
534 Dresser Tower
Houston, TX 77002

Contact: Howard S. Dial, Division
Vice President
Phone: 713-782-9220

MAY ENTERPRISES, INC.
P. O. Box 6606
Odessa, TX 79760

Contact: Ken Stewart, President
Phone: 915-362-2368

MWM CONTRACTING CORP.
347 North Main Street
Milford, MI 48042

Contact: Joe McCullough
Phone: 313-685-9350
313-685-1201

NATIONAL SEAL CO, INC.
7701 East Kellogg
Wichita, KS 67202

Contact: John W. Owen
Phone: 316-681-1931

PACIFIC LININGS, INC.
P.O. Drawer GGGG
Indio, CA 92201

Contact: John Blatt, President
Phone: 714-347-0828

PLASTI-STEEL, INC.
3588 West 13th Street
Vickers-KSB&T Building
Wichita, KS 67203

Contact: M. C. Green, President
Phone: 316-262-6861

SCHLEGEL AREA SYSTEMS, INC
P. O. Box 23197
Rochester, NY 14692

Contact: James M. Price
Phone: 716-244-1000

STA-FLEX CORP.
16 Post Road
Greenland, NH 03840

Contact: Lou Peloquin
4917 New Ramsey Court
San Jose, CA 95136
Phone: 408-224-0604

THE THURSTON WALLACE CO.
5470 East Evans Ave.
Denver, CO 80222

Contact: Hank Thurston, President
Phone: 303-758-2232

TRI STATE CONSTRUCTION
959 108th Avenue, N.E.
Belleview, WA 98004

Contact: Joe Agostino
Phone: 206-455-2570

UNIT LINER CO
P. O. Box 789
Shawnee, OK 74884

Contact: J. A. Hendershot,
President
Phone: 405-275-4600

UNIVERSAL LININGS, INC.
P. O. Box 315
Haverford, PA 19041

Contact: David M. Small, President
Phone: 215-649-3600

FABRICATORS WHO ALSO INSTALL:

McKittrick Mud
Synflex Industries, Inc.

B. BENTONITE PRODUCERS AND SUPPLIERS

AMERICAN COLLOID COMPANY
5100 Suffield Court
Skokie, IL 60077

Contact: Nick Kesslering
Ryan F. McKendrick
Phone: 312-583-0400

ARCHER-DANIELS-MIDLAND
P.O. Box 15166
Commerce Station
Minneapolis, MN 55415

Contact:
Phone: 612-371-3400

ASHLAND CHEMICAL
9450 Midwest Avenue
Cleveland, OH 44125

Contact:
Phone: 216-587-2230

DOWELL
1150 North Utica Street
P. O. Box 21
Tulsa, OK 74102

Contact: Chris Parks
Mining and Construction
Technical Services
Phone: 918-560-2972

DRESSER MINERALS
P.O. Box 6504
Houston, TX 77005

Contact:
Phone: 713-972-2670

INTERNATIONAL MINERALS &
CHEMICAL CORP.
IMC FOUNDRY PRODUCTS
17350 Ryan Road
Detroit, MI 48212

Contact: G. Alther
Phone: 313-368-6000

CHARLES PFIZER & CO.
235 East 42nd Street
New York, NY 10017

Contact:
Phone: 212-573-2323

WILBUR ELLIS CO.
P.O. Box 1286
Fresno, CA 93715

Contact:
Phone: 209-226-1934

WYO-BEN PRODUCTS, INC.
P.O. Box 1979
Billings, MT 59103

Contact:
Phone: 406-252-6351

C. OTHER LINER MATERIALS

THE ASPHALT INSTITUTE
Asphalt Institute Building
College Park, MD 20740

Contact:
Phone: 301-277-2458

CHEVRON, USA, INC.
Asphalt Division
P. O. Box 7643
San Francisco, CA 94120

Contact: Kenneth Coleman
K. D. Coleman Co
P. O. Box 414
Santa Clara, CA 95052
Phone: 408-244-8948

I.U. MANAGEMENT SYSTEMS, INC.
1500 Walnut Street
Philadelphia, PA 19102

Contact:
Phone: 215-985-660

MICHELLE CORPORATION
Division of Weychem Canada Limited
P. O. Box 4794
Charleston Heights, SC 29405

Contact: F. Weyrich, President
Phone: 803-554-4033

PHILLIPS PETROLEUM COMPANY
Commercial Development Division
Bartlesville, OK 74004

Contact: Floyd H. Holland
Phone: 918-661-6428

PORTLAND CEMENT ASSOCIATION
Old Orchard Road
Skokie, IL 60076

Contact:
Phone 312-066-6200

D. MISCELLANEOUS ORGANIZATIONS IN LINER INDUSTRY

HOVATER-WAY ENGINEERS, INC.
23011 Moulton Parkway, Suite F-5
Laguna Hills, CA 92653

Contact: Louis R. Hovater
Phone:

Type of service: Design engineering, specializing in membrane liners.

LINING MATERIALS
23011 Moulton Parkway, Suite F-4
Laguna Hills, CA 92653

Contact: George J. Miller,
General Manager
Phone: 714-581-9292

Type of service: Supplier of a variety of lining materials.

LIQUID CONTAINMENT SYSTEMS
P. O. Box 324
South Holland, IL 60473

Contact: Jack Moreland, President
Phone: 312-468-2500

Type of service: Design, planning, engineering, and installation of liners.

NATIONAL SANITATION FOUNDATION
NSF Building
Ann Arbor, MI 48105

Contact: Gary W. Sherlaw, Director
Standard Development
Phone: 313-769-8010

Type of service: Developing national specifications for membrane liners.

SARNAFIL CANADA, LTD.
75 Horner Avenue
Toronto, Ontario, Canada

Contact: Ursala Schenck
Phone: 416-259-9203

Type of service: Developing, marketing, manufacturing, and selling membrane liners.

WATERPROOFING SYSTEMS, INC.
P.O. Box 2182
Santa Barbara, CA 91320

Contact: O.E. Hengsen
Phone: 805-963-6785

Type of service: Consulting, engineering, and contracting of various lining materials.

APPENDIX III
SELECTED LINER TEST METHODS

A. IMMERSION TEST OF MEMBRANE LINER MATERIALS FOR COMPATIBILITY WITH WASTES.

B. POUCH TEST FOR PERMEABILITY OF POLYMERIC MEMBRANE LINERS.

C. TUB TEST OF POLYMERIC MEMBRANE LINERS.

D. TEST METHOD FOR THE PERMEABILITY OF COMPACTED CLAY SOILS (CONSTANT ELEVATED PRESSURE METHOD).

A. IMMERSION TEST OF MEMBRANE LINER MATERIALS FOR COMPATIBILITY WITH WASTES

Scope:

This test is designed to assess, under accelerated conditions, the compatibility of polymeric membrane liner materials with specific wastes.

Summary of Method:

Samples of the polymeric liner materials are fully immersed in a representative sample of the waste to be contained. Over a range of exposure periods, tests are run to determine the change in weight, dimensions, composition, and physical properties of the liner material as function of time. One immersion sample is required for each immersion time or exposure condition.

Equipment and Supplies:

Equipment:

- Exposure tank - minimum one gallon or four litre capacity, with provision for hanging specimens so that they do not touch bottom or sides of tank, or each other. Suggested arrangements are glass rods across top of tank, or stainless steel hooks fastened to tank lid.
- Stress-strain machine suitable for measuring tensile strength,tear resistance and puncture resistance.
- Jig for testing puncture resistance for use with FTMS 101B, Method 2065.
- Oven at 105±2°C.
- Analytical balance.
- Apparatus for running extractables, e.g. Soxhlet extractor or ASTM D297 rubber extraction apparatus. All-glass apparatus is preferred for chlorinated solvents or for liners which contain chlorine, because materials containing chlorine sometimes corrode the tin condensers of the D297 apparatus.

Supplies:

- Labels and hangers for specimens, of materials known to be resistant to the specific waste. Hangers of stainless steel wire, and tags made of 50 mil polypropylene, embossed with machinist's numbering dies and fastened with stainless steel wire, are resistant to most wastes.

Procedure:

1. Obtain representative sample of the waste fluid. Note if fluid classifies or separates.

2. Perform the following tests on unexposed samples of the polymeric membrane liner materials:

    2.1. Percent volatiles (2 h @ 105°C), ASTM D297 (modified).

    2.2. Percent extractables with suitable solvent (see Table III-A-1), ASTM D3421.

    2.3. Tear resistance, machine and transverse directions, five specimens each direction, ASTM D624, Die C.

    2.4. Puncture resistance, five specimens, FTMS 101B, Method 2065.

    2.5. Tensile tests in two directions, five specimens each direction, ASTM D412.

        - Tensile strength, psi
        - Elongation at break, %.
        - Tensile set after break, %.
        - Stress at 100, 200, and 300% elongation, psi.

    2.6. Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

TABLE III-A-1. SOLVENTS FOR EXTRACTION OF POLYMERIC MEMBRANES

Polymer type	Extraction solvent[a]
Butyl rubber	Methyl ethyl ketone
Chlorinated polyethylene (CPE)	n-Heptane
Elasticized polyolefin	Methyl ethyl ketone
Chlorosulfonated polyethylene (CSPE)	Acetone
Neoprene	Acetone
Polyester elastomer	Methyl ethyl ketone
Polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol

[a] Selected to remove oil, plasticizer, and other soluble constituents without dissolving the polymer.

3. Cut a 6 x 8 inch piece of the lining material for each waste and each exposure period. Measure the following:

    3.1 Gage thickness, mil or mm - average of the four corners.
    3.2. Mass, g - to one hundreth of a gram.
    3.3 Length, cm - average of the lengths of the two sides.
    3.4. Width, cm - average of the widths of the two ends.

4. Label the test specimen with a plastic identification tag and hang in sample of the waste fluid by a wire hanger.

5. At the end of the exposure, remove specimen from waste. Wipe off as much waste as possible and rinse well with water. Place wet specimen in a labelled polyethylene bag to prevent the specimen from drying out.

6. To test the immersed sample, remove wire hangers and identification label from specimen. Wipe off any remaining waste and rinse with deionized water. Blot specimen dry and measure the following:

   6.1. Thickness, mil or mm.
   6.2. Mass, g.
   6.3. Length, cm.
   6.4. Width, cm.

   The specimen should be returned to its polyethylene bag as soon as possible to prevent any loss of absorbed water.

7. Perform the following tests on the exposed specimen:

   7.1 Percent volatiles (2 h @ 105°C), ASTM D297 (modified).
   7.2. Percent extractables, ASTM D3421.
   7.3 Tear resistance, machine and transverse directions, two specimens each direction, ASTM D624, Die C.
   7.4. Puncture resistance, two specimens, FTMS 101B, Method 2065.
   7.5 Tensile tests, machine and transverse directions, three specimens each direction, ASTM D412.
      - Tensile strength, psi.
      - Elongation at break, %.
      - Tensile set after break, %.
      - Stress at 100, 200, and 300% elongation, psi
   7.6 Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

   See Figure III-A-1 for a suggested cutting pattern.

8. Summarize the results as follows:

   8.1. Percent change in thickness.
   8.2. Percent change in mass.
   8.3. Percent change in area.
   8.4 Percent volatiles of unexposed and exposed liner material.
   8.5. Percent extractables of unexposed and exposed liner material.
   8.6. Percent retention of physical properties.
   8.7. Change, in points, of hardness reading.

9. Tests should be run over a range of exposure times. For compatiblity studies, the suggested range of exposure times is 0.5, 1, 2, and 4 months.

10. Fresh waste fluid may be required to maintain concentration of constituents or to simulate actual service conditions.

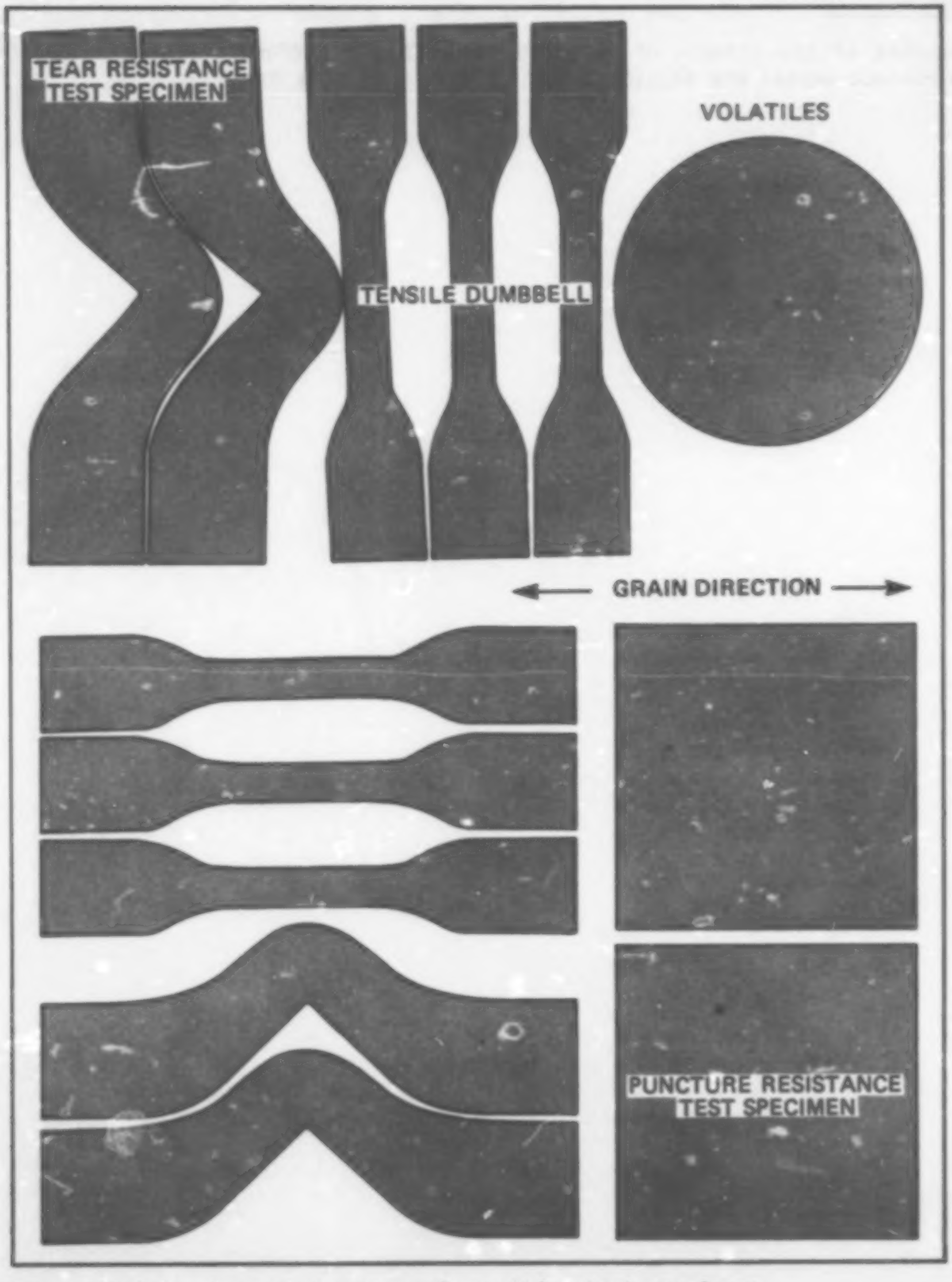

TEAR RESISTANCE
TEST SPECIMEN
TENSILE DUMBBELL
VOLATILES
GRAIN DIRECTION
PUNCTURE RESISTANCE
TEST SPECIMEN

Figure III-A-1. Suggested pattern for cutting test specimens.

Test Results:

Examples of the effects of extended immersion of different lining materials in various wastes are illustrated in Chapter 4 of this Manual.

B. POUCH TEST FOR PERMEABILITY OF POLYMERIC MEMBRANE LINERS

Scope

This test was designed to measure the permeability of polymeric membrane materials to water and to various constituents of the wastes.

Summary of Method

Waste is put into a small bag fabricated of the liner material to be tested. This test bag is placed in a larger plastic bag containing deionized water. A concentration gradient is thus created across the liner which results in the movement by osmosis of water and ions and other dissolved constituents through the membrane. Weight and conductivity measurements are taken periodically to determine, respectively, the extent of movement of water into the membrane and the extent to which the waste leaks through the membrane.

Equipment and Supplies

Equipment

- Heat sealer, P.A.C. Bag Sealer Model 12 PI with long interval timers.
- Clamp made of two 0.5" square steel bars 4" long with 0.25" bolts and thumb screws located 0.5" from the ends.
- Wooden racks with compartments 1" x 8" x 6.5" deep.
- pH meter.
- Conductivity meter, e.g. Industrial Instruments Conductivity Bridge Model RC 16B2.
- Balance, 1000 g capacity, accurate to ± 0.1g.
- Stress-strain machine suitable for measuring tensile strength, tear resistance, and puncture resistance.
- Jig for measuring puncture resistance for use with FTMS 101B, Method 2065.
- Apparatus for running extractables, e.g. Soxhlet extractor or ASTM D297 rubber extraction apparatus. All-glass apparatus is preferred for chlorinated solvents or for liners which contain chlorine, because materials containing chlorine sometimes corrode the tin condensers of the D297 apparatus.

Supplies:

- Deionized or distilled water.

- Polybutylene bags with a wall thickness of 6 to 10 mils, and with dimensions of 8.5" x 10 ".

- Cotton swabs.

- Medium size binder clips.

Procedure:

1. Perform the following tests on unexposed samples of the polymeric membrane liner materials:

   a. Percent volatiles (2 h @ 105°C), ASTM D297 (modified).

   b. Percent extractables with suitable solvent (see Table III-B-1), ASTM D3421.

   c. Tear resistance, machine and transverse directions, five specimens each direction, ASTM D624, Die C.

   d. Puncture resistance, five specimens, FTMS 101B, Method 2065.

   e. Tensile tests, machine and transverse directions, five specimens each direction, ASTM D412.

      - Tensile strength, psi.
      - Elongation at break, %.
      - Tensile set after break, %.
      - Stress at 100, 200, and 300% elongation, psi.

   f. Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

TABLE III-B-1. SOLVENTS FOR EXTRACTION OF POLYMERIC MEMBRANES

Polymer type	Extraction solvent[a]
Butyl rubber	Methyl ethyl ketone
Chlorinated polyethylene (CPE)	n-Heptane
Elasticized polyolefin	Methyl ethyl ketone
Chlorosulfonated polyethylene (CSPE)	Acetone
Neoprene	Acetone
Polyester elastomer	Methyl ethyl ketone
Polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol

[a] Selected to remove oil, plasticizer, and other soluble constituents, without dissolving the polymer.

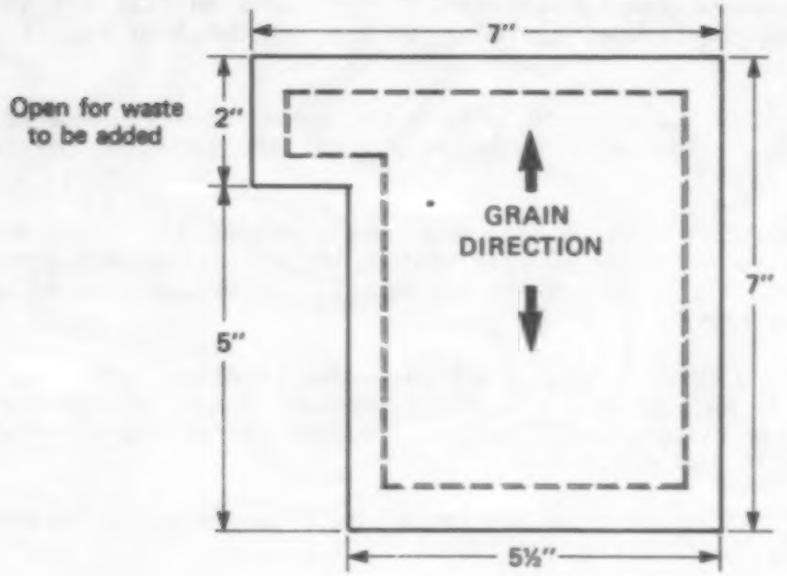


Figure III-B-1. Pattern for cutting pieces of membrane for making the bags. Dotted line indicates the heat seal of the bag. The inside dimension of the bag is 4.5" x 5.75".

2. Cut two pieces of liner as shown in Figure III-B-1.

3. Heat seal the two pieces of liner together leaving the neck open. Measure the inside dimensions of the bag to the nearest millimeter and record the calculated area and dry weight of bag.

4. Test the bag for leaks by filling with deionized water. Close the neck of the bag with binder clips. Weigh the bag and water again after one week to test for loss by leakage. The emptied bag is then ready for filling with waste.

5. Measure pH and conductivity of the selected waste.

6. Add one hundred grams of the waste through a funnel. Close the bag by applying the clamp at the base of the neck. Carefully dry the inside of the neck with cotton swabs. Heat seal the neck opening. Remove the clamp, and record the weight of the filled bag.

7. Place the bag in a polybutylene bag with 600 mL of deionized water. Fold the opening of the polybutylene bag over and secure with binder clips (Figure III-B-2).

8. Store the assembly in a compartment of the racks so that the sealed osmotic bag is covered by water in the polybutylene bag (Figure III-B-3).

9. For testing during exposure, remove the osmotic bag, blot dry, and weigh. Measure the pH and conductivity of the water in the outer bag.

10. These measurements should be made weekly during the first month, bi-monthly during the next five months, decreasing to once a month, and eventually to once every two months. It is important to watch for leaking bags.

11. The exposure period should end when the increase in weight and conductivity have reached a level of constant change or when the bag material has changed drastically. The expected exposure period is six months to one year.

12. When a bag has failed or at the end of the exposure period, dismantle and test by the following procedure:

    12.1. Weigh the inner bag.

    12.2. Determine pH and conductivity of the water in the outer bag.

    12.3. Measure length and width between seams of osmotic bag.

    12.4. Empty osmotic bag and determine pH and conductivity of waste.

    12.5. Dismantle bag at seams, leaving bottom seam together.

    12.6. Prepare specimens for physical tests. A suggested pattern for dieing out specimens is shown in Figure III-B-4.

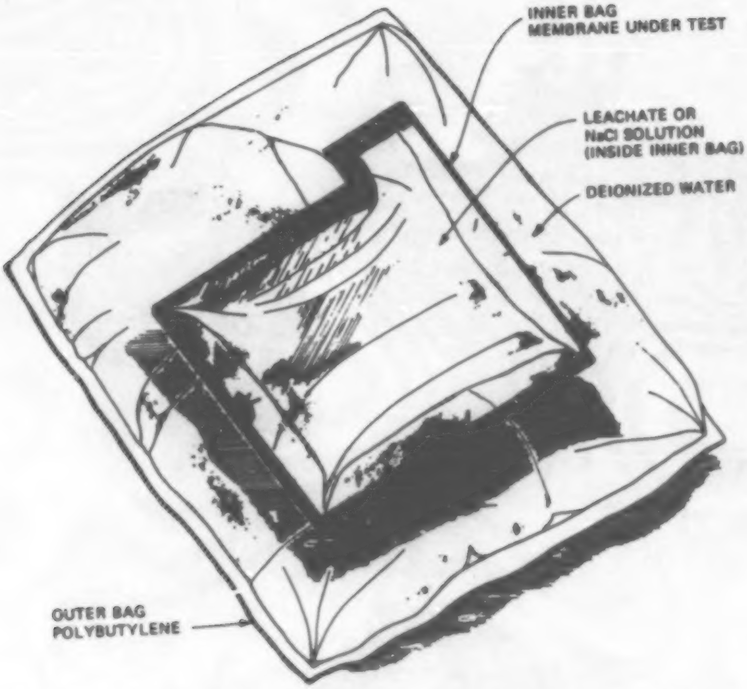
    12.7. Perform the following tests:

        12.7.1. Percent volatiles (2h @ 105°C), ASTM D297 (modified).

        12.7.2. Percent extractables, ASTM D3421.

        12.7.3. Tear resistance, machine and transverse direction, two specimens each direction, ASTM D624, Die C.

        12.7.4. Puncture resistance, two specimens, FTMS 101B, Method 2065.



INNER BAG
MEMBRANE UNDER TEST
LEACHATE OR
NaCl SOLUTION
(INSIDE INNER BAG)
DEIONIZED WATER
OUTER BAG
POLYBUTYLENE

Figure III-B-2. Schematic of bag assembly, showing inner bag made of membrane material under test. The inner bag is filled with waste fluid and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water. The water in the outer bag is monitored for pH and conductivity; the inner bag is monitored for weight change.

12.7.5. Tensile tests, machine and transverse directions, three specimens each direction, ASTM D412.

- Tensile strength, psi.
- Elongation at break, %.
- Tensile set after break, %.
- Stress at 100, 200 and 300% elongation, psi.

12.7.6. Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

13. The following data should be reported.

13.1. Properties of the unexposed liner materials.

13.2. Properties of liner materials at the end of test.

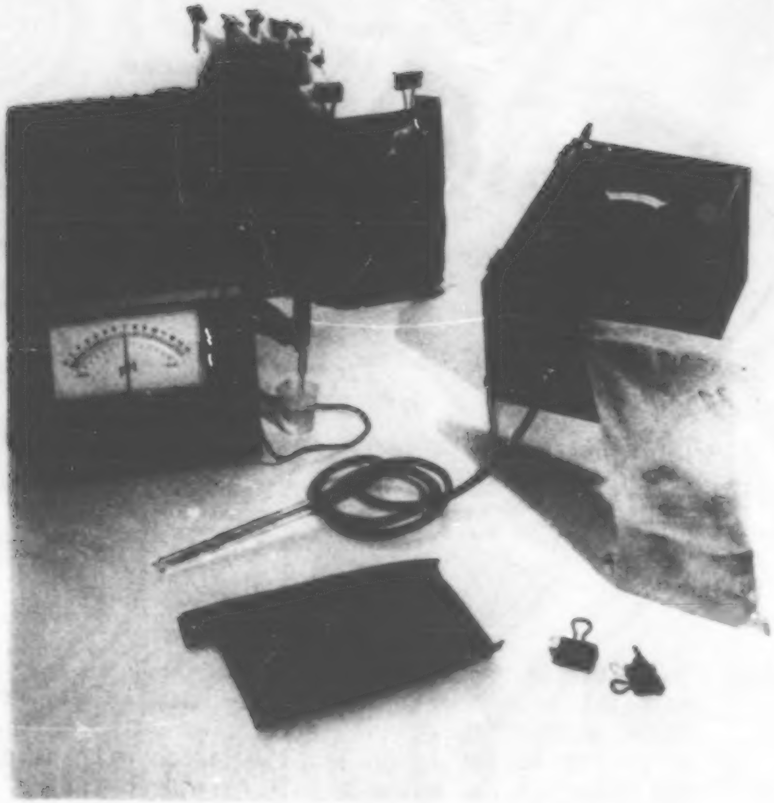


Figure III-B-3. Bag and auxiliary equipment for determining permeability of membrane liner materials to water and constituents of waste fluids.

13.3. Percent retention of properties during the test.

13.4. Electrical conductivity as function of time.

13.5. Increase in weight of bag as a function of time.

13.6. pH value as a function of time.

Test Results:

Typical test results obtained in the bag test are presented in Chapter 4.

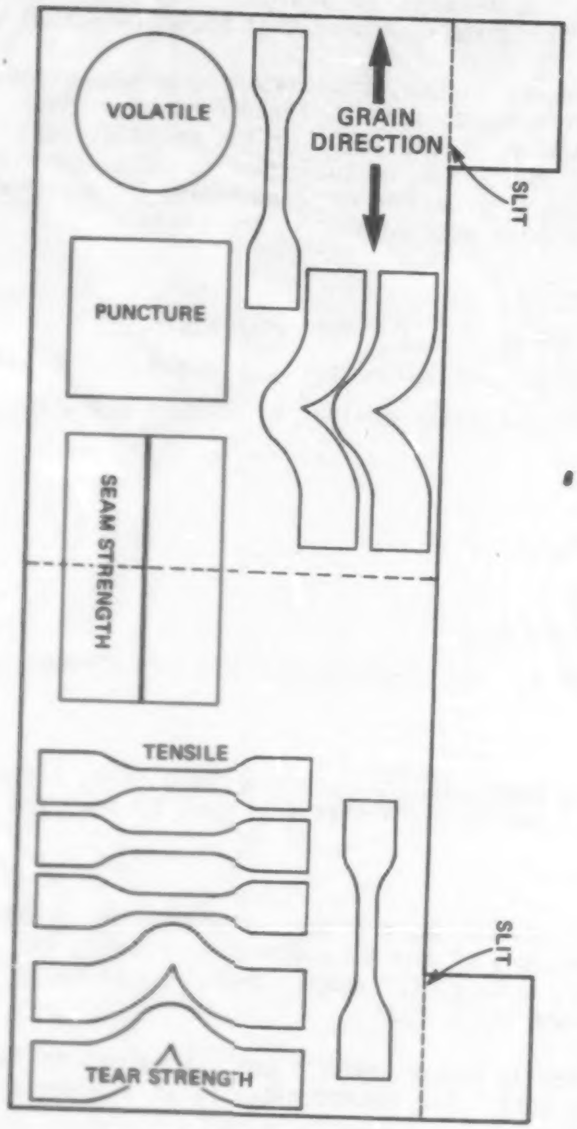

VOLATILE
GRAIN DIRECTION
SLIT
PUNCTURE
SEAM STRENGTH
TENSILE
SLIT
TEAR STRENGTH

Figure III-8-4. Suggested pattern for dieing out test specimens from exposed bag.

C. TUB TEST OF POLYMERIC MEMBRANE LINERS

Scope:

The purpose of the tub test is to evaluate flexible membrane liner materials under conditions which simulate those that occur in actual service.

The effects of exposure to sun, temperature changes, ozone, and other weather factors can be evaluated, as well as the effect of a given waste on a specific liner. The fluctuation of the level of the waste is particularly significant in that an area of the liner is subjected to both the effects of the waste and weather. This alternating of conditions is especially harsh on liner materials and is usually encountered in the field.

Equipment and Supplies:

- Plywood to construct tubs and catch basin
- Pipe fittings and corks for tub and catch basin drains and plugs
- Meter stick or similar device to measure waste depth
- Thermometers
- pH meter
- Conductivity meter
- Drying oven
- Analytical balance
- Other equipment for chemical analyses, as needed.

Test specimen:

Piece of membrane liner, incorporating a field seam, large enough to fold over edges of the tub. Approximate size four feet by four feet.

Test Procedure:

The plywood tubs should be rectangular with sides sloping outward at a 1:2 slope. The dimensions of the tubs should be roughly 14" x 9" at the base, 25" x 20" at the top, and ca. 11" deep. Useful catch basin dimensions are 8 ft x 6 ft x 4 in (Figure III-C-1).

The liner specimen is draped over a tub and folded to fit the inside contours and edges of the tubs. The excess material is allowed to hang freely over the edges of the tub.

Tensile strength, elongation at break, modulus, and tear strength of unexposed liner materials are determined. Physical testing is again performed on the liner specimens at the end of the exposure period.

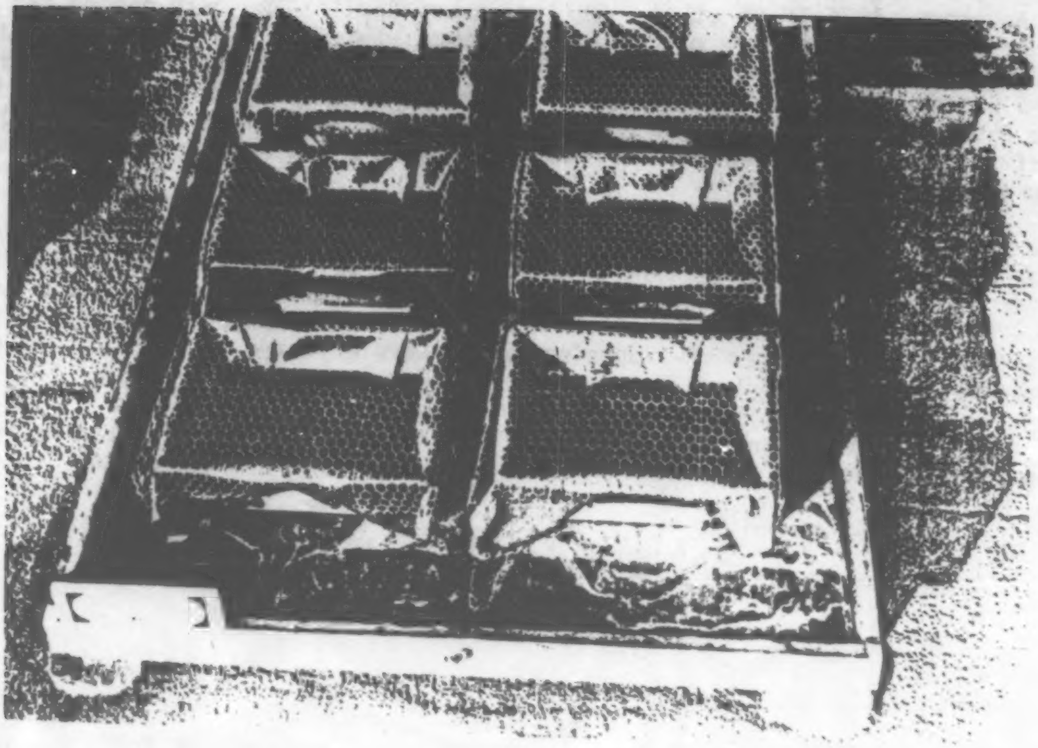


Figure III-C-1. The open exposure tubs lined with polymeric membranes and partially filled with hazardous wastes. They are covered with chicken wire and placed in a shallow basin lined with an elasticized polyolefin membrane. During rainy weather these cells are protected by a corrugated plastic cover (Haxo and White, 1977)

The tubs are filled from 3/4 to 7/8 full with wastes. The liquid level is allowed to fluctuate about 4 inches. During the exposure period the tub liners are inspected visually for cracking, opening of seams, and other forms of liner deterioration. The waste levels and temperatures are measured and recorded at regular intervals. Water is added when levels become too low. An oily waste which generally has a film of water at the surface tends to accumulate water (from dew) which does not evaporate significantly. Water, or actually an oil-water mixture, should be pumped from the bottom of these tubs to maintain liquid levels and prevent overflows of the waste. The oil-water mixture removed may be analyzed for pH, electrical conductivity, percent solids, and other parameters as appropriate. The water in the catch basin is also monitored for pH and conductivity as a possible indication of leakage from the tubs containing highly acidic or highly alkaline wastes.

Status of Tub Exposure Tests Underway in Oakland, California:

Long-term tub exposure tests on a roof in Oakland, California, were started in November, 1976 (Haxo et al., 1977). As of April 1980, only one of the 12 liner specimens that were placed in this test had failed. The tests consisted of 12 tubs utilizing four wastes (spent caustic, alkaline slop water, nitric acid waste, and a waste oil) and nine liner materials (elasticized polyolefin, two PVC's, polyester elastomer, butyl rubber, neoprene, EPDM, CSPE, and CPE). Most of the liners have swelled to some degree after an exposure period of approximately 3.5 years.

The elasticized polyolefin exposed to the waste oil developed cracks and leaked on the 517th day of exposure. This liner was observed to have swelled after one month of exposure and the swelling apparently continued at a very slow rate until failure. The elasticized polyolefin membrane developed in the waste/sun interface area, two openings which were oriented along folds in the membrane.

On removal from the tub, physical tests of the exposed liner were run at four exposure locations:

- Under waste only
- In waste/shade zone
- In shade only
- In waste/sunlight zone

The waste/sunlight zone provided the harshest environment for the liner material, as shown by the test results in Table III-C-1.

No other liner failure had occurred to April 1980, though deterioration of the exposed liners was evident. The seams in the EPDM liner exposed to nitric acid wastes had weakened and the caulking appeared cracked, but no leaking had been detected. The PVC liner below the acid waste has become hard. The liners tended to swell more at folds as well as in the waste/sun zone, indicating that both situations should be regularly examined on in-service liners. At the sharp corners, the butyl rubber liner was ozone cracking.

TABLE III-C-1.
FAILED ELASTICIZED POLYOLEFIN LINER
EXPOSED TO SATURATED AND UNSATURATED OILS IN OPEN TUB[a]

Test	Original value	% Retention of property of exposure to Waste only	Waste + sun	Waste + shade	Shade only
Thickness, mils	23	113	113	113	98
Tensile strength, psi	2590	47	38	45	97
Elongation at break, %	665	89	81	83	99
Tensile set, %	445	76	72	74	100
S-100, psi	875	68	59	65	110
S-200, psi	970	64	46	63	107
Puncture resistance, lb.	26.3	97	73	70	135
Elongation, inches	0.97	130	122	113	142

[a] Exposure time: 506 days from 11/2/76 tO 3/23/78.

D. TEST METHOD FOR THE PERMEABILITY OF COMPACTED CLAY SOILS

(Constant Elevated Pressure Method)

Introduction

To assess the suitability of compacted clayey soils for the lining of waste disposal facilities, the primary laboratory measurement is saturated hydraulic conductivity or permeability. Such a measurement should be made on a specimen of the soil that has been remolded and compacted in the range of optimum moisture content to achieve the maximum density possible for a given compactive effort. ASTM Method D698 should be used for determining a soil moisture-density relation.

Clays compacted at optimum moisture content have the potential to reach permeability values as low as 10^{-10} cm sec. However, permeability values in the range of 10^{-5} cm sec^{-1} to 10^{-8} cm sec^{-1} are more probable.

Testing should be continued until the permeability stabilizes, which may require the passing of one or more pore volumes of a standard 0.01N $CaSO_4$ leachate. For these reasons, it is necessary to use increased pressure to increase the hydraulic gradient and reduce the time length of the test (Bennett, 1966). Trapped air is a common cause for artificially low permeability values (Christiansen et al., 1946). An increase of pressure reduces air trapped in the core by increasing the weight of gas that will dissolve in water flowing through the specimen (Jones, 1960). The higher pressures will also reduce the volume of the remaining air pockets. Backpressuring is necessary in very low permeability soils to dissolve air in the specimens. The use of deaerated water is desirable.

For a given waste-clay liner combination, there are two fluids that may alter the permeability of the liner: (1) the fluids present in the waste (primary leachate) and (2) the fluids generated by water percolating through the waste (secondary leachate). When only solids are placed in the confinement, only secondary leachate need be considered. The permeameter used for testing the influence of leachate on the permeability of the clay liner must be capable of safely operating with hazardous materials including industrial solvents, volatile compounds, corrosive acids, and strong bases.

Soil permeability tests must be carefully performed if they are to be accurate. Leaks, volatile losses, or channel flow along the interface of the permeameter and soil will greatly affect permeability values (Bowles, 1978).

To avoid channel formation, the clay should be allowed to seat at low pressure. By allowing two to three inches of standard leachate (0.01 N $CaSO_4$ or $CaCl_2$) to stand on the core for 24 hours, an effective seat is obtained for the top few millimeters of the clay core. This thin layer will prevent bulk flow and the rest of the core should adequately seal when the leachate is forced into the soil at elevated pressures.

In order to facilitate ease of duplication of the test apparatus, the permeameter is based on readily available and easily modified components. Figure

III-D-1 illustrates the modified compaction permeameter which is based on the standard compaction permeameter that is available through most soil testing supply houses. All components are in common with the standard permeameter except for the enlarged fluid chamber, extended studs, and high pressure fittings.

General Comments:

For use with fluids other than water, all gaskets should be Teflon. To avoid leakage around the gaskets, all metal surfaces against which the gaskets are seated should be wiped clean of grit. All components should withstand continuous operation at pressures up to 60 psi.

To limit the volume for diffusive mixing of leachate samples after they have passed through the clay core, the fluid outlet part should be fitted with an adapter to a small (1/8 inch) inside diameter Teflon tubing. The use of translucent Teflon at the permeameter outlet provides a convenient window with which to monitor the expulsion of entrapped air. Standard leachate should be passed through the permeameter until there are no air bubbles visible in the outlet tubing. If soil piping occurs, eluted soil clays will be visible either clinging to the inside walls of the outlet tubing or as a suspension in the collected flow samples.

Volatile losses may occur during sample delivery from the outlet tubing to the sample bottles in the fraction collector. To limit these volatile losses, the top of each sample collection container should be fitted with a long stem funnel and the fraction collector should be placed in an air-tight cooled compartment. This is also desirable where the fluids being tested may present a health hazard to exposed laboratory personnel.

When volatile hazardous chemicals are used, the entire test apparatus should be fitted into a vented hood. This precaution is insurance against worker injury in case of a gasket blow out. If testing of several cores simultaneously is desired, each pressure line must have its own cut-off valve to prevent the complete shut down of the test in the case of loss of pressure in a single specimen. With several specimens producing leachate, it may be desirable to have an automatic fraction collector. This is especially useful with long-term tests. Over the course of a one-month test, it may not be convenient to change the sample bottles every few hours, twenty four hours a day.

Calculations:

This test is to determine the intrinsic permeability of a compacted clay by a constant-elevated pressure head method for the flow of any permeant through compacted clay soils. The equation applicable to the test is Darcy's law as modified to normalize permeability values as they are affected by the permeant's viscosity and density:

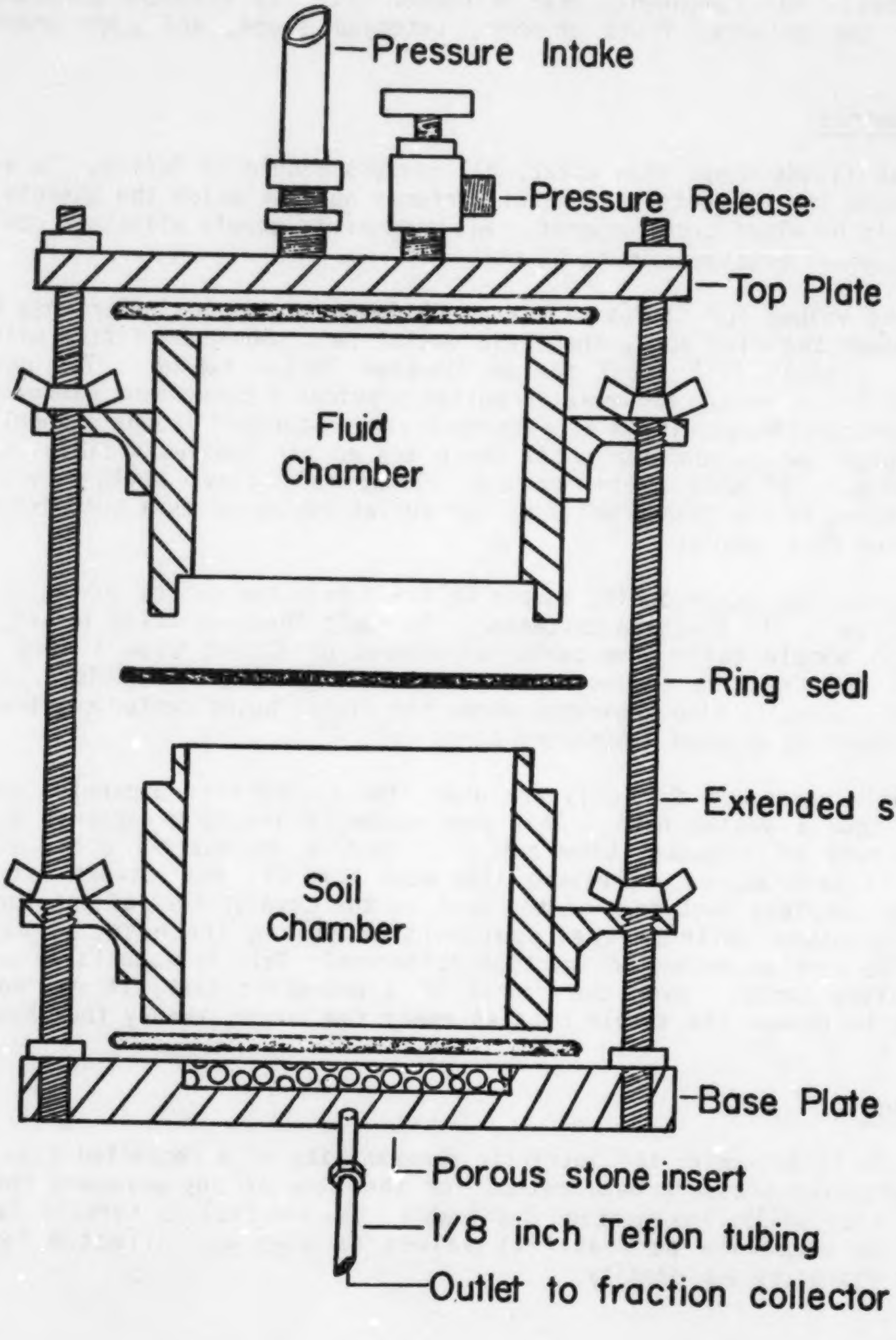

Pressure Intake
Pressure Release
Top Plate
Fluid Chamber
Ring seal
Extended stud
Soil Chamber
Base Plate
Porous stone insert
1/8 inch Teflon tubing
Outlet to fraction collector

Figure III-D-1. Modified Compaction Permeameter.

$$K = \frac{V\ n\ L}{p\ g\ A\ t\ (L + H)}$$

K = intrinsic permeability (cm^2)

V = volume of flow (cm^3) in time t

n = permeant viscosity (dyne sec. cm^{-2})

p = permeant density (g cm^{-3})

g = gravitational constant (cm sec^{-2})

A = cross-sectional area of flow (cm^2)

t = time (sec.)

L = length of soil core (cm)

H = pressure (cm of H_2O)

The sign is negative to indicate the direction of flow.

Equipment Requirements

1. Soil crusher (C-2 Laboratory Crusher).
2. Soil grinder (Hewitt Soil Grinder).
3. 2 mm sieve (CB-810 brass sieves).
4. Moisture cans (LT-30 tin sample boxes).
5. Balance capable of weighing 20 kgs. (L-500 heavy duty balance)
6. 105°C drying oven to determine water content of soil samples.
7. Compaction molds (CN-405 Standard Compaction Mold).
8. Compaction hammer (CN-4230 Mechanical Compactor).
9. Steel straight edge.
10. Permeameter bases and top plates (K-611 Permeameter Adapter).
11. A source of compressed air with a water trap, regulator and pressure meter.
12. A fraction collector with automatic timer for collection of samples over time (Brinkmann Linear II Fraction Collector with a multiple distribution head).
13. An air tight, cooled chamber to limit volatile loss of samples during and after sampling
14. A vented hood to hold the compaction permeameters and chamber containing the fraction collector. (This is a safety precaution to limit exposure of laboratory personnel to the hazardous chemicals used in the studies.)

Note: Equipment in Items 1, 3, 4, 5, 7, 8, and 10 can be obtained from Soil Test, Inc.; equipment in Item 2 can obtained from B. Hewitt Welding and Repair.

Test Procedure

1. Obtain sufficient clay soil to be tested. Break the soil down to golf ball size clods and lay them out to air dry.

2. Grind the air dried soil and pass it through a 2 mm sieve.

3. Mix the sieved soil thoroughly, and divide into two lots of equal weight. Each lot of soil should be placed in air tight containers at room temperature until the time of use. Each lot should be enough soil to prepare up to 10 compaction molds (50 kg. will provide for some spillage losses assuming a mold volume of about 1,000 cm^3).

4. Use one lot of the soil to determine the moisture density relations of the soil by following the ASTM Method D-698.

5. Use a second lot of the soil to prepare compaction molds at optimum moisture content.

6. Fit a valve on top of the permeameter top plate with pressure fittings and connect it to a source of air pressure via copper tubing. Place a water trap, pressure regulator and pressure gage in line between the air pressure source and permeameter. The water trap should go between the pressure source and regulator to prevent build up of debris on the membrane in the regulator. The pressure gage should be located between the regulator and a pressure manifold to the permeameters so that the hydraulic head being exerted on the clay cores may be monitored.

7. Place sufficient volume of the leaching solution in the chamber above the compacted soil.

8. Apply pressure to force at least one pore volume of the standard leachate (0.01 N $CaSO_4$ or CaCl) through the clay cores. After the intrinsic permeability values are stable and less than 10^{-10} cm^2 equivalent to permeability value of 10^{-5} cm sec^{-1} at 25°C, release the pressure, disassemble the permeameter and examine the core.

9. If the clay core has shrunk, it is unsuitable as a clay liner.

10. If the clay has expanded into the upper mold, remove the excess soil with a straight edge by cutting so as to not smear the clay surface. Reweigh the core to determine its density and then remount it on the permeameter.

11. Repressurize the permeameter and pass standard leachate until the intrinsic permeability value stabilizes again less than 10^{-10} cm^2 equivalent to a permeability value of 1.1×10^{-5}cm sec^{-1} at 25°C.

12. Remove the remaining standard leachate from eight of the fluid chambers and replace it on duplicate cores with each of two wastes or waste leachates to be tested.

13. If after passage of one pore volume of the various leachates, the intrinsic permeability values of the cores are still above 10^{-10} cm^2, disassemble the permeameter and re-examine the cores.

14. If the clay core has shrunk, it is unsuitable as a clay liner for that waste.

15. If the clay core has expanded, repeat step 10 then proceed to step 17.

16. If the clay has not changed volume, remount it on the parameters.

17. Repressurize the permeameter and pass at least one pore volume of the standard leachate. If its intrinsic permeability has climbed above 10^{-10} cm^2 (ca. 1.1 x 10^{-5} cm s^{-1}) the clay is not suitable for containing the waste. If the intrinsic permeability values measured on a waste's primary and secondary leachate have consistently stayed below 10^{-10} cm^2, proceed to Step 18.

18. Examine the translucent Teflon outlet tube for signs of soil particle migration out of the core. If there is evidence of soil migration, pass at least one more pore volume to observe if this internal erosion of the core continues. If it continues after the two pore volumes of standard leachate have passed, the clay is unsuitable for that waste. If the soil migration stops, at least one pore volume of the standard leachate should be passed to assure that the core stabilization is permanent and then proceed to Step 19.

19. If there is no sign of soil migration, depressurize the system and extrude the clay cores from their molds to examine them for signs of cracking, internal erosion, soil piping, clay dissolution, structural changes, or any other difference from the control cores (those having received only standard leachate).

If there is no sign that the cores have deteriorated, the clay should be suitable for lining the disposal facility to contain that waste.

Note: For references, see Chapter 4.

APPENDIX IV
INSTALLATION OF FLEXIBLE POLYMERIC MEMBRANE LINERS

The installation of flexible membrane liners requires a significant planning effort prior to construction. This planning effort must include consideration of the storage and security of all necessary equipment, installation equipment, manpower requirements, the placement operation, field seaming, anchoring and sealing, quality control, inspection, and protection of placed liners. These considerations are discussed in detail in this Appendix.

IV.1 On-site Storage of Materials and Equipment.

Items requiring storage will include the liner materials and all equipment necessary for installation. Figure IV-1 shows liner material packaged and shipped to the site. Most liner material is packaged in folded panels or rolls which may weigh from 2,000 to 5,000 pounds each. All membrane liners should be stored out of sunlight if possible to prevent their degradation and to minimize blocking. Blocking occurs when the liner material sticks together, causing delamination or ripping when the roll is unrolled onto the subgrade. Figure IV-2 shows the result of blocking of a reinforced liner, with the scrim exposed. This damage will have to be repaired. Liners are shipped rolled or accordion folded in cardboard boxes and placed on wooden pallets. The liner material can thus be moved from the storage site to the construction site by means of a fork-lift truck, or some other suitable piece of equipment, without damage.

An important consideration in the storage of all equipment and liner materials at the site is prevention of vandalism and theft. This can be accomplished by erecting a temporary fence or placing the material in an existing secured area. The need for an elaborate storage system can be minimized if the job can be planned so that all equipment and materials necessary can be brought to the site, and installation begun immediately after receipt of liner materials and location of equipment at the site.

IV.2 Installation Equipment

Necessary equipment needed to install flexible membrane liners depends on the type of liner material to be installed, the complexity of the job with respect to side slope steepness, the number of penetrations, the number of seals required, and the length of installation time anticipated. Some means to move the liner material from storage to the impoundment site is necessary. A fork-lift truck is very useful for this purpose, though other pieces of equipment, such as a backhoe or front-end loader, can also be used. High-density polyethylene liner material is brought to the site in rolls rather than pallets and requires a crane or front-end loader for moving to the installation site.

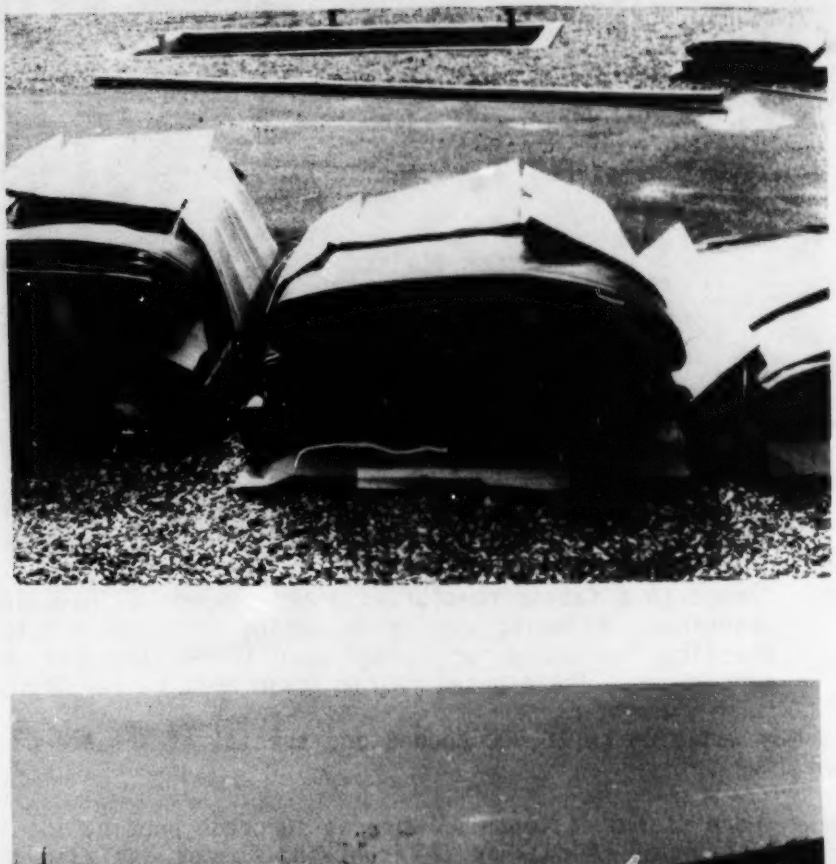


Figure IV-1. Liner panels are shipped to the site on wooden pallets either rolled or accordion folded.

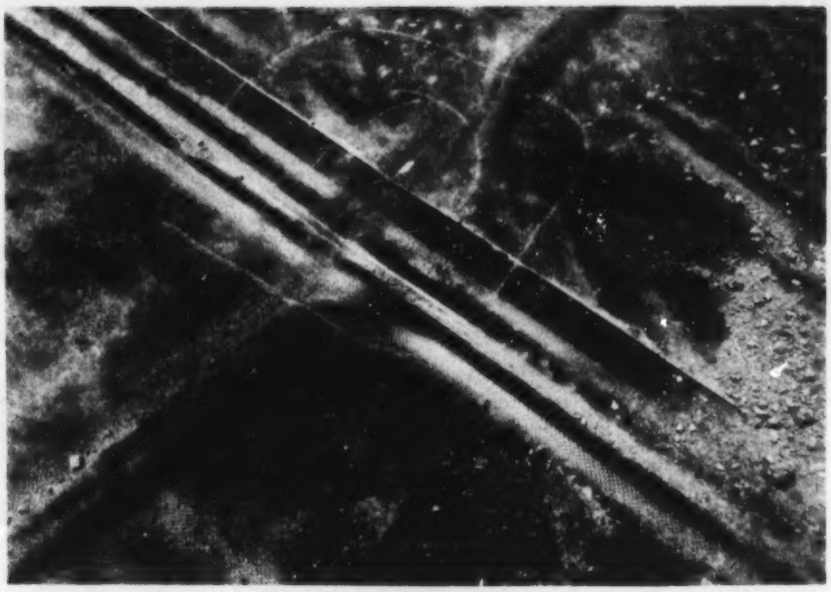


Figure IV-2. Damage to a fabric reinforced liner caused by "blocking" of the sheeting. Blocking can occur during shipping or storage when sheeting is rolled or folded and sticks together under warm conditions. The exposed fabric scrim must be repaired.

These rolls may weigh up to 10,000 pounds and special straps are used to move them (Figure IV-3).

A backhoe may prove useful if touch up work on subgrade preparation is required during installation. A backhoe or front-end loader can also be used to move sand to the top of the slopes so that sand bags can be filled to prevent the wind from damaging panels that are placed prior to seaming.

The majority of liner materials are solvent seamed in the field. Hand rollers are used to obtain a good surface bond. High-density polyethylene is heat-welded and requires specialized equipment. This includes an automatic welder which can be raised or lowered along the side slope of the impoundment. A hand welder is also used. Figure IV-4 shows the hand welder and the automatic welder being lowered down the side slope by a winch.

For liner materials which require the use of rollers in the field seaming, a board at least one inch thick, 12 inches wide, and up to 12 feet long should be available for each seaming crew to use. This board provides support during seaming and is placed under the overlap of the liner material. As seaming progresses, the board is slid along underneath the seam to provide a good seaming surface. These boards normally have ropes tied to the front so that they can be pulled along underneath the seam as the seaming crew moves from the middle of the panel to the ends. Figure IV-5 shows the rope attached to a seaming board which is properly located beneath the seam.

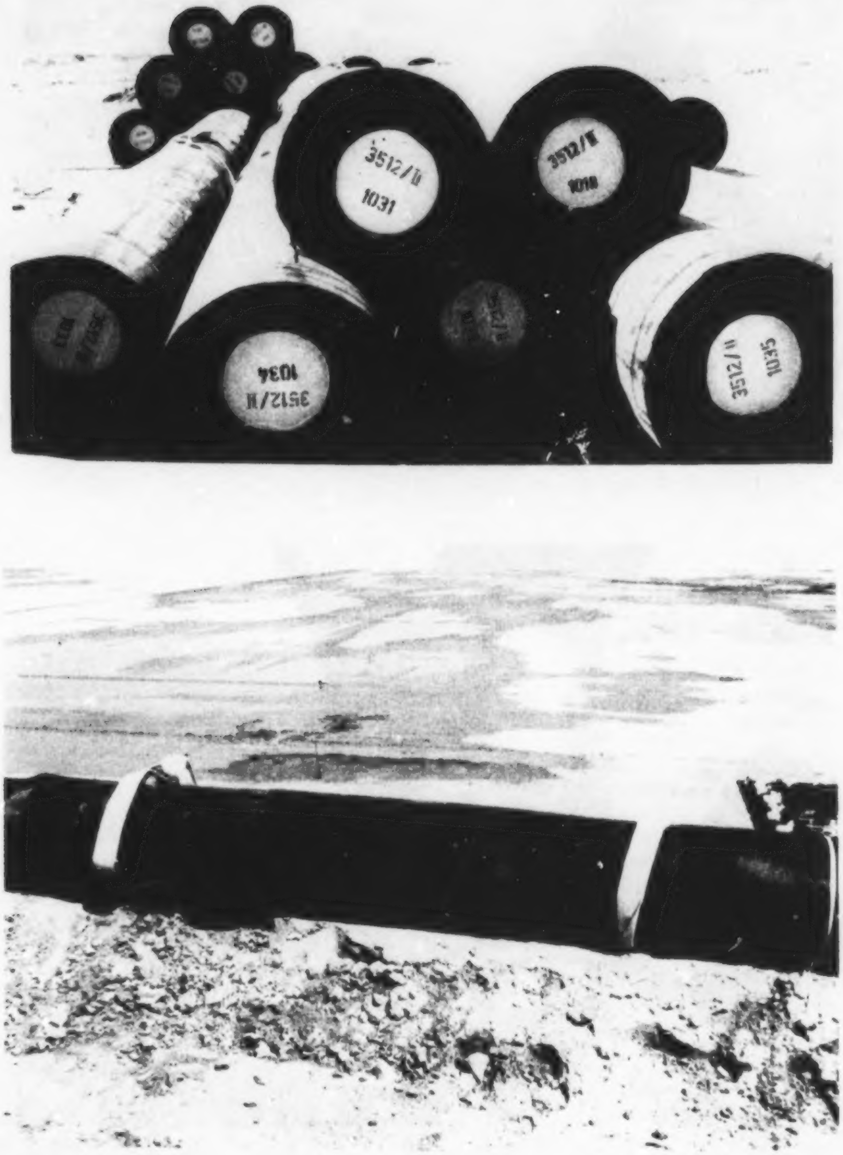
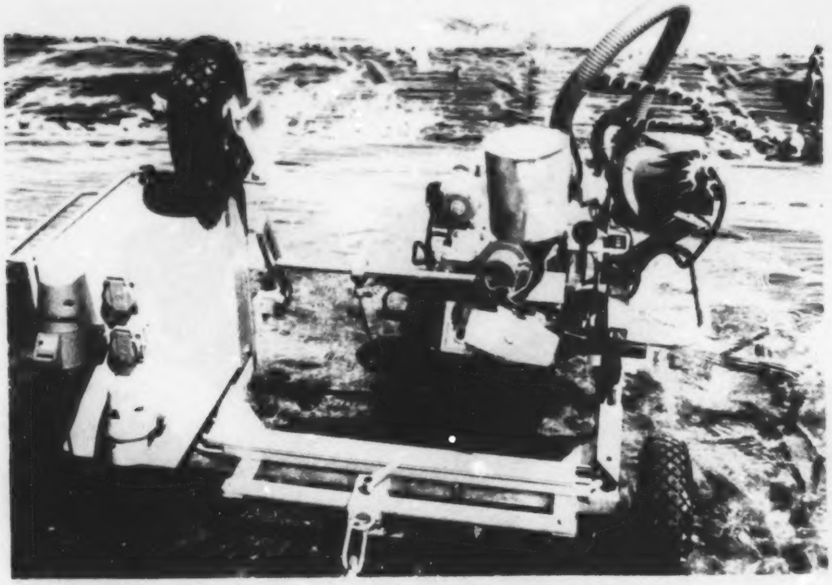

3512/II
1031
3512/II
1010
3512/II
1034
3512/II
1035

Figure IV-3. High-density polyethylene (HDPE) is shipped to the site rolled onto drums. Each roll may weigh up to five tons.



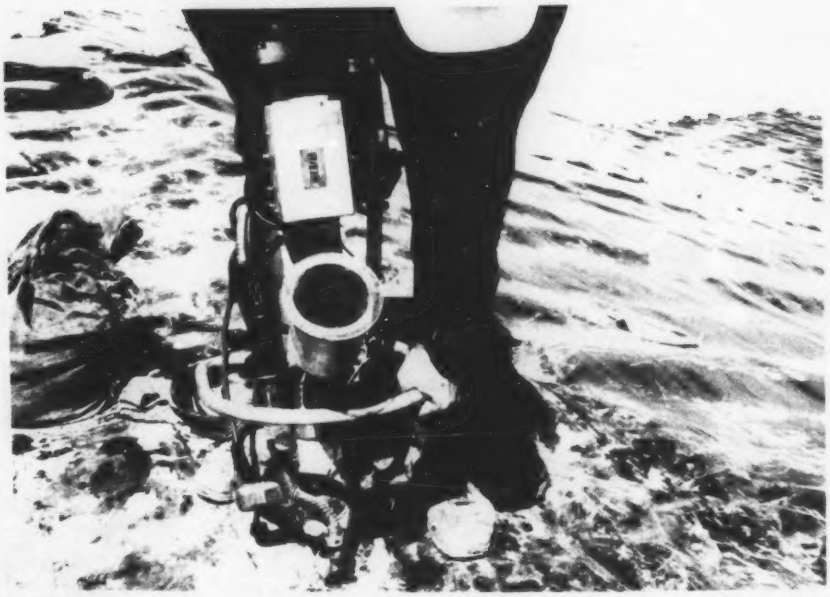


Figure IV-4. Special equipment for seaming of high-density polyethylene (HDPE). An automatic welder is shown above; a hand held welder is shown below. With both devices molten HDPE is extruded between the overlap of the two sheets being seamed.

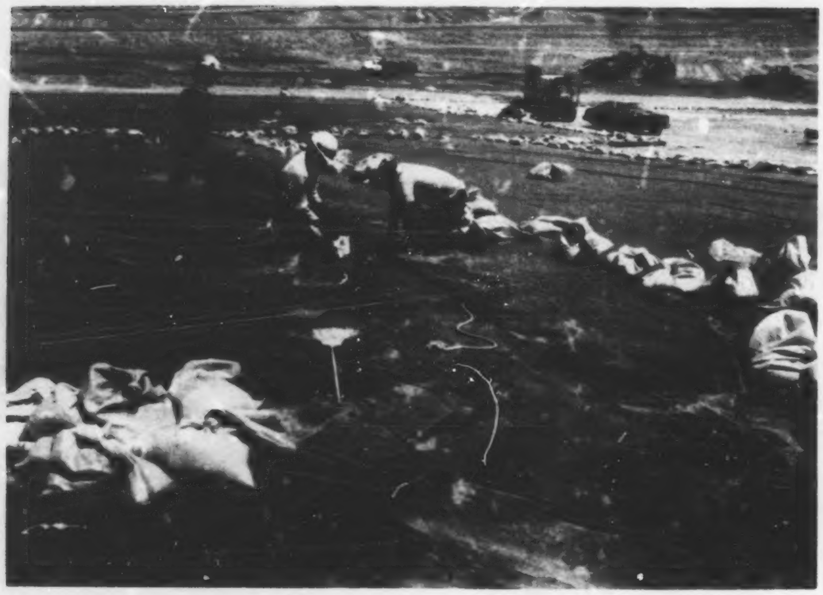
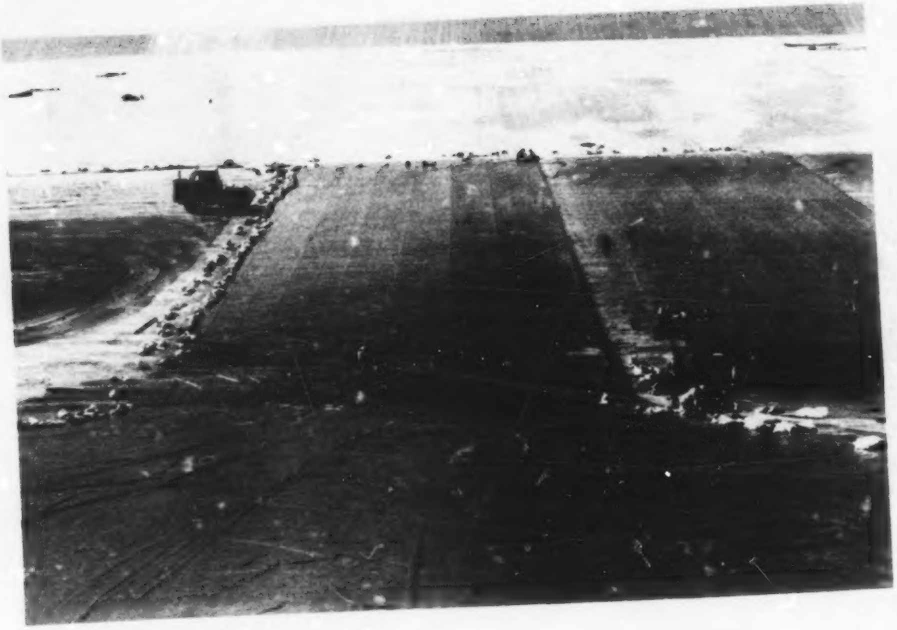


Figure IV-5. This crew is using a board for support under the area being seamed. The board is pulled along under the liner with the rope shown in the picture.

It is necessary to have some means to control the effects of wind on panels which have been laid on the subgrade. This can be accomplished using old tires, or more commonly, sandbags placed every five to ten feet along unseamed edges. Figure IV-6 shows how sandbags can be used to prevent wind damage to liner material.

Many of the liner materials require surface cleaning where the seam is to be made prior to actual seaming. Therefore, a sufficient supply of clean cotton rags must be available to the seaming crew. In addition, natural brushes and stainless steel scouring pads are necessary, particularly for seaming CSPE, as the surface cure must be removed prior to seaming. Heat guns should be available when solvent seaming is to take place. These guns provide a means to bring the liner material to a suitable temperature in the event the ambient temperatures are below 60° F. Figure IV-7 shows the use of a heat gun to warm the liner. If trichlorethylene is used for seaming, a heat gun should be used with extreme caution, as toxic phosgene gas can be formed. Seaming crews using trichloroethylene should not smoke on the job as inhalation of smoking materials in the presence of trichloroethylene produces the same phosgene gas. Respirators are often needed, especially when crew members must work in confined areas and use solvents. An electric generator and sufficient extension cords are necessary if heat guns are used. A crayon should be available for marking the location of seams prior to the application of solvents. Additional equipment needed for the installation of liners includes caulking compounds and caulking guns, pails for washing solvents, paint brushes or



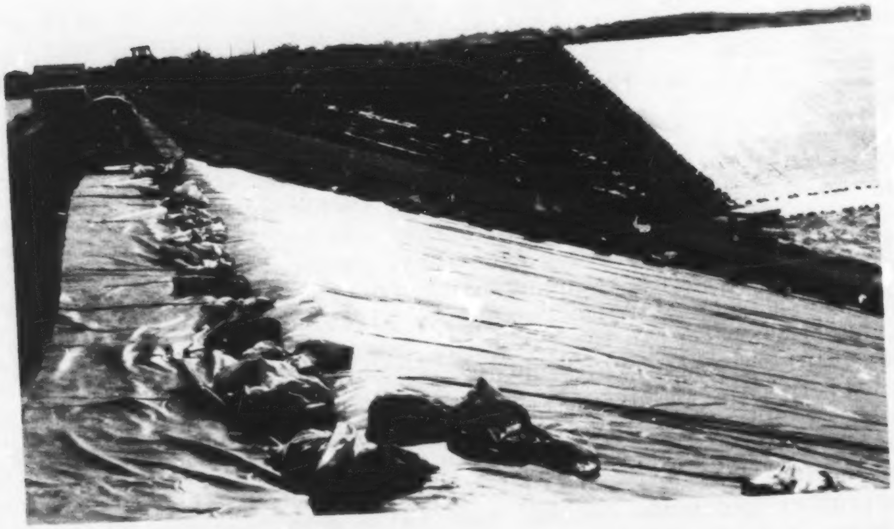


Figure IV-6. Sandbags are often used to anchor unseamed sheets of liner and thus prevent wind damage.

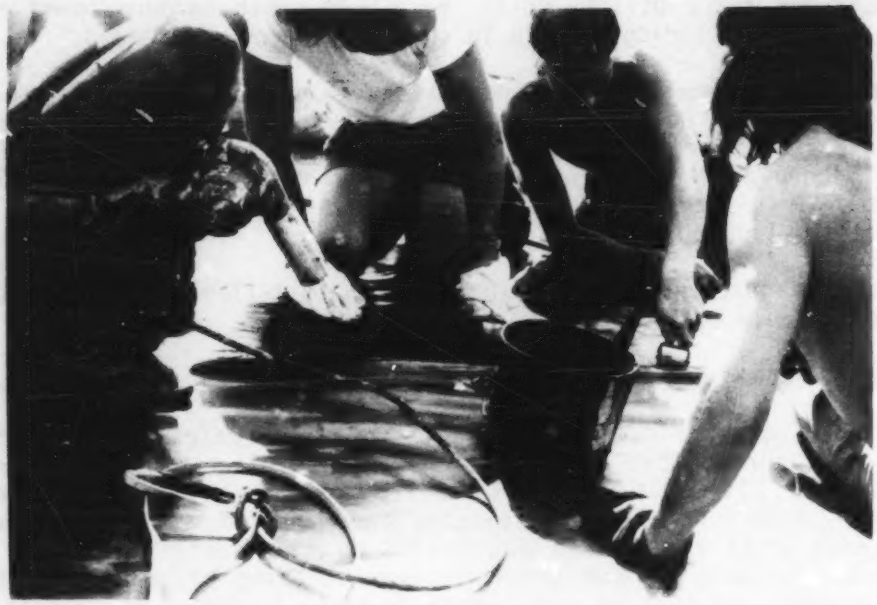


Figure IV-7. Heat guns are used to facilitate field seaming.

other applicators, solvent resistant gloves, safety goggles for men working with solvents, knee pads, shoes with flat soles to prevent damage to the liner, scissors and a utility knife, hand-held earth tampers, hand rakes and shovels, stakes and string to help in the spotting of the panels.

Large sections or panels of a liner are often moved across the subgrade by field crews. Wooden dowel rods should be provided to the field crew to use in moving panels without stretching the edges which will be seamed. These dowel rods are placed on the edge of the panel; the panel is then rolled onto the dowel rod. This provides a handle so that the panels can be moved without stretching the liner.

A list of the equipment often required for installation of membrane liners is presented in Table IV-1.

IV.3 Manpower Requirements

Manpower requirement for the installation of liner materials is obviously a function of the rate that the installer wants to place panels and accomplish field seaming. Typically, installation contractors will have anywhere from five to ten people on site when placing one panel at a time. Generally, a crew foreman will direct the activities of the field crew. He may not directly participate in the unrolling and spotting of panels or in field seaming. However, he must be experienced in installation of the specific liner material.

Crew size requirements also depend on the complexity of the installation and the experience of the field crew. If the majority of the crew members are recruited locally, they probably will require training during installation. At the present time, the trend is toward having installation contractors retain field supervisors who travel from job site to job site. Large jobs where crews perform specific tasks may involve many people. This occurs where one crew unrolls panels, another crew spots the panels, and a third crew performs all field seaming. Crew sizes also depend on the number of structures or penetrations in the facility. For example, if three or four concrete pillars are located within the area of one panel, this situation will require more manpower than if the panel is to be placed on a flat subgrade. In many instances, the owner of the facility may provide necessary manpower on an as-needed basis to the installation contractor. This arrangement will minimize the direct cost of installation to the owner, as excess work loads can be fulfilled with temporary labor.

IV.4 Liner Placement

Table IV-2 enumerates principal considerations that installers should follow in placing a specific liner. Before moving panels from the storage site to the installation location a number of tasks must be performed. The anchor trench around the perimeter of the installation should be completed. The dirt excavated from the anchor trench should be raked smooth so that the panels can be unrolled along and parallel to the anchor trench in the width direction. Other things that must be accomplished prior to panel spotting are: (1) the

TABLE IV-1. EQUIPMENT AND MATERIALS FOR INSTALLATION OF FLEXIBLE MEMBRANE LINERS

Item	Use
Fork lift	To move liner panels and backfill anchor trenches.
Tires, sandbags	To anchor unseamed panels to prevent wind damage.
Proper adhesives	To make field seams and seal liner around concrete or steel penetrations.
Portable electric generator	To operate heat guns or lighting for working at night.
Air lance	Quality control testing of field seams.
Hand-held earth tampers	To smooth subgrade as necessary.
Miscellaneous materials:	For field seaming.
- Adhesive applicators (paint brushes, caulking guns, rollers, etc.).	
- Liner preparation equipment: clean rags, scrub brushes, scouring pads, pails for solvent, hard surface rollers, seaming support board, heat guns, crayons for marking, dowels for pulling panels, stakes and chalk line, steel measuring tape, scissors and utility knives, electrical extension cords (for heat guns).	
Field crew equipment:	For field crew when making seams.
- Safety goggles, solvent resistant gloves, knee pads, respirators, soft soled shoes.	
First aid kit	In case of accidents.
Air compressor	Supply air that might be needed when working with solvents, and for air lance.

TABLE IV-2. CONSIDERATIONS DURING LINER PLACEMENT

Follow manufacturers' recommended procedures for adhesive system, seam overlap, and sealing to concrete.

Use a qualified installation contractor having experience with membrane liner installation, preferably the generic type of liner being installed.

Plan and implement a quality control program which will help insure that the liner meets specification and the job is installed per specifications. Inspection should be documented for review and record keeping.

Installation should be done during dry, moderately warm weather if possible.

Subgrade should be firm, flat, and free of sharp rocks or debris.

subgrade should be raked smooth or compacted if necessary; (2) there should be no standing water in the impoundment; (3) any concrete structures that must be seamed around should be prepared prior to unrolling of any panels; (4) if skirts are to be used around footings on concrete structures, these must be in place prior to the beginning of panel placement; (5) any outflow or inflow structures or other appurtenances should be in place.

Placement often begins with the unfolding or rolling of the panels lengthwise as shown in Figure IV-8. The panels are then unfolded in the width direction, either down the side slope or across the floor (Figure IV-9). The field crew then begins to position or "spot" the panel into its proper location (Figure IV-10). As panels are spotted and seamed together, sand bags are placed as shown in Figure IV-11. The instructions on the boxes containing the liner must be followed to assure the panels are unrolled in the proper direction with the correct side exposed for seaming (Figure IV-12). The panels should be pulled relatively smooth over the subgrade (Figure IV-13). If the subgrade is smooth and compacted, then the liner should be relatively flat on the subgrade. However, sufficient slack must be left in the material to accommodate any possible shrinkage due to temperature changes.

IV-5 Field Seaming

The panels should be unfolded and spotted so that a sufficient seam overlap of the adjacent panel is maintained. Figure IV-14 shows two examples of proper overlap. Seam overlap varies with liner manufacturer and the liner type. Recommended overlaps vary from 4 to 12 inches. Figure IV-15 illustrates typical factory and field seams.

Field seaming is a critical factor in flexible membrane liner placement. The liner manufacturers have recommended procedures and adhesive systems for achieving successful field seams. If the manufacturer does not have a recommended bonding system, then the use of that liner material should be questioned. Generally three methods are used to seam materials in the field. These

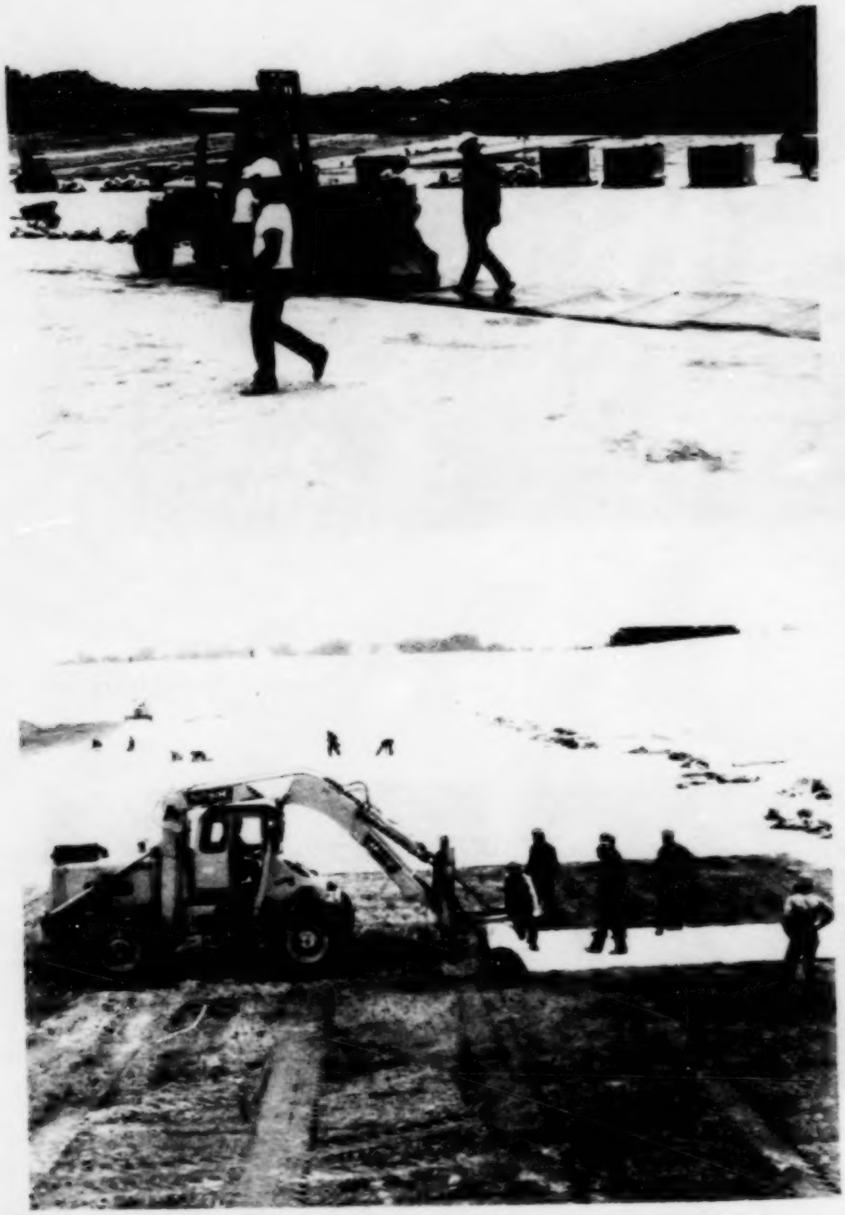


Figure IV-8. The panels of liner membrane are unfolded or unrolled.

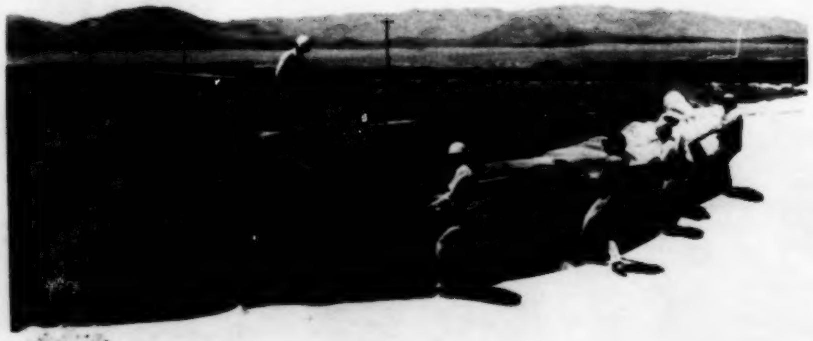


Figure IV-9. Workmen "pull" the panel across the subgrade. This step may be difficult to accomplish during windy conditions.

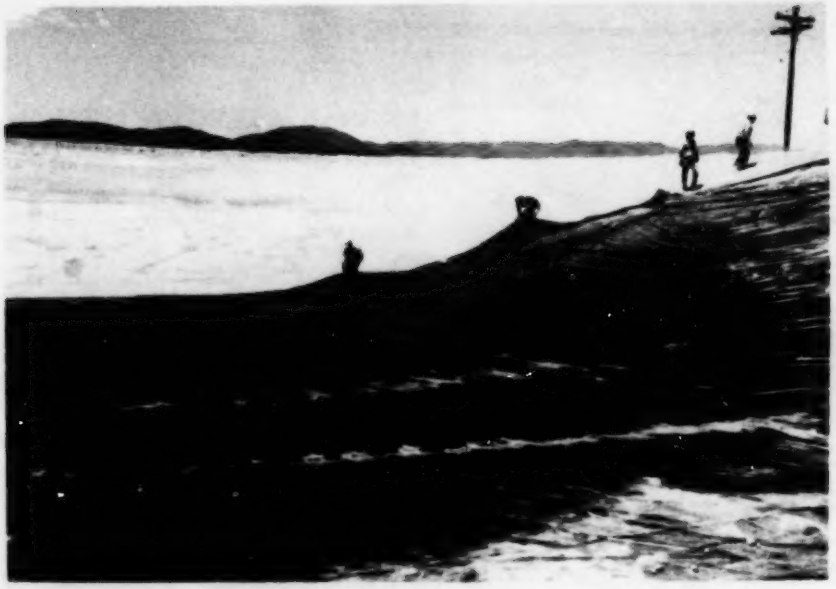
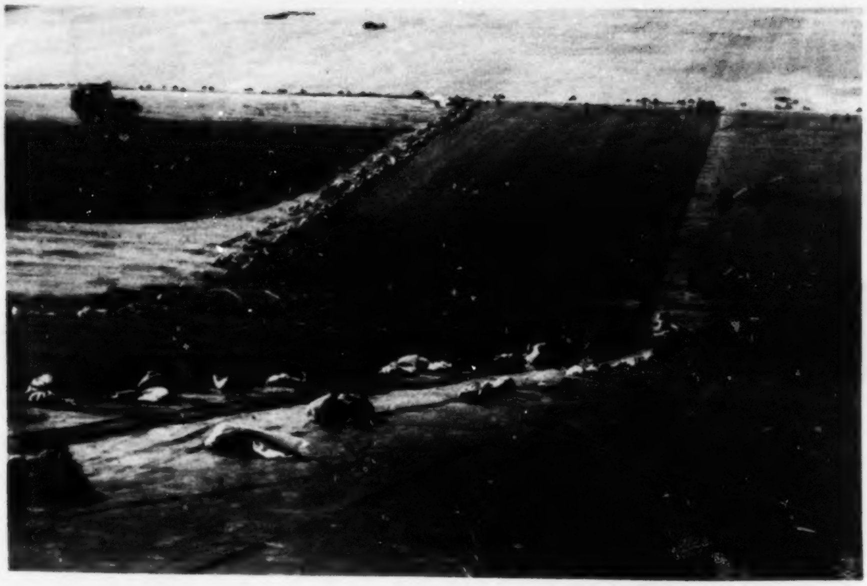


Figure IV-10. Once a panel has been unfolded, the crew "spots" or positions it in the proper location.



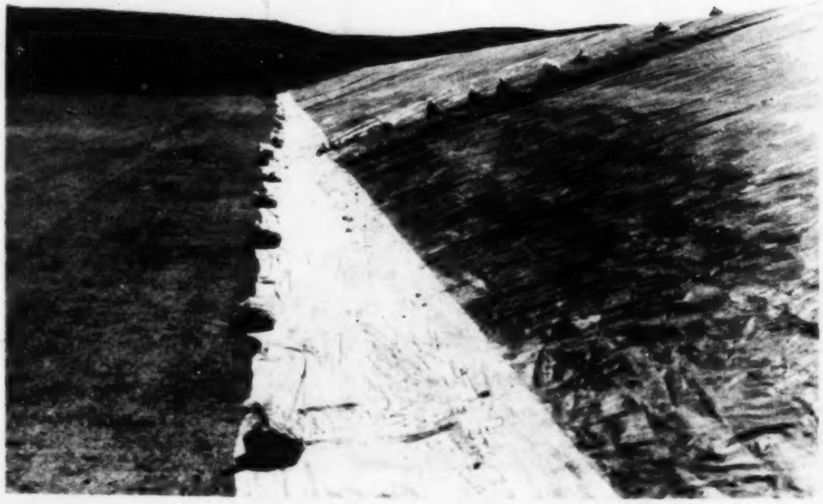


Figure IV-11. Sandbags are placed along the edges to be seamed. This prevents wind damage.

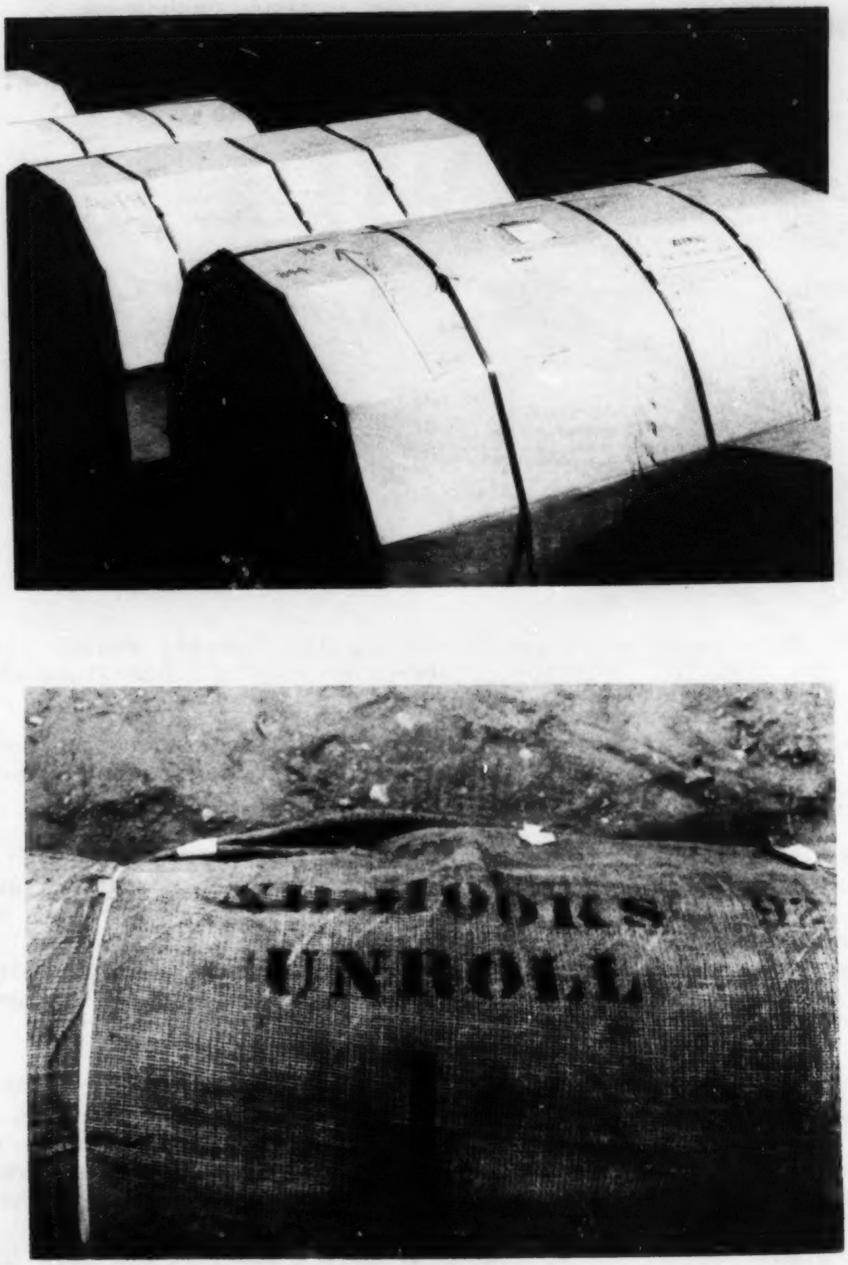


Figure IV-12. The instructions for unrolling liner panels are clearly shown on each container.

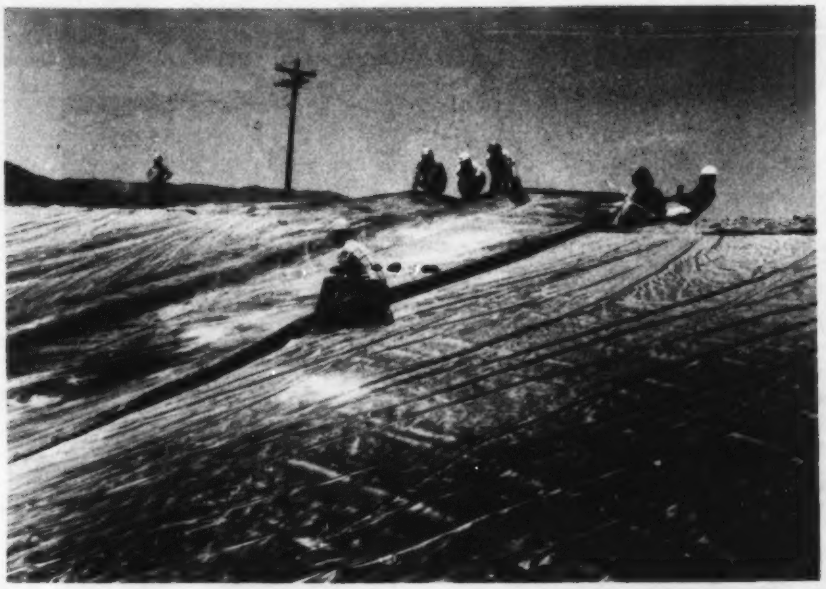


Figure IV-13. Each panel must be pulled smooth, leaving enough slack to accommodate anticipated shrinkage due to temperature changes.

are bodied solvent, heat, or contact adhesive. Solvent and contact adhesive systems are the most prevalent. The installation contractor should use the manufacturer's recommended procedure.

The integrity of the field seam is determined by many factors. The most important factor is that the adhesive system used must be compatible with the liner material and suitable for use under actual field conditions. As previously indicated, the liner manufacturers have specified adhesive systems that work best for their products. These systems normally have limitations with regard to temperature. Most adhesive systems work best at temperatures greater than 60°F.

Another important factor in field seam integrity is that the surfaces to be seamed are clean and dry when the field seams are made. The presence of any moisture can interfere with the curing and bonding characteristics of the adhesive used. The presence of any dirt or foreign material can jeopardize the seam strength and provide a path for fluid to migrate through the seam.

Since pressure must be applied to a seam after the adhesive has been applied, the liner ideally should rest on a dry, hard, and flat surface for rolling Many installers use a board such as described in Section 2 of this appendix. This board is placed underneath the overlap of the liner material. Overlaps can be anywhere from 4 to 12 inches wide, depending on the type of material and the conditions under which seaming takes place. Once the board is placed

Figure IV-14. Sufficient seam overlap must be maintained. Manufacturers usually specify minimum overlap for field seams.

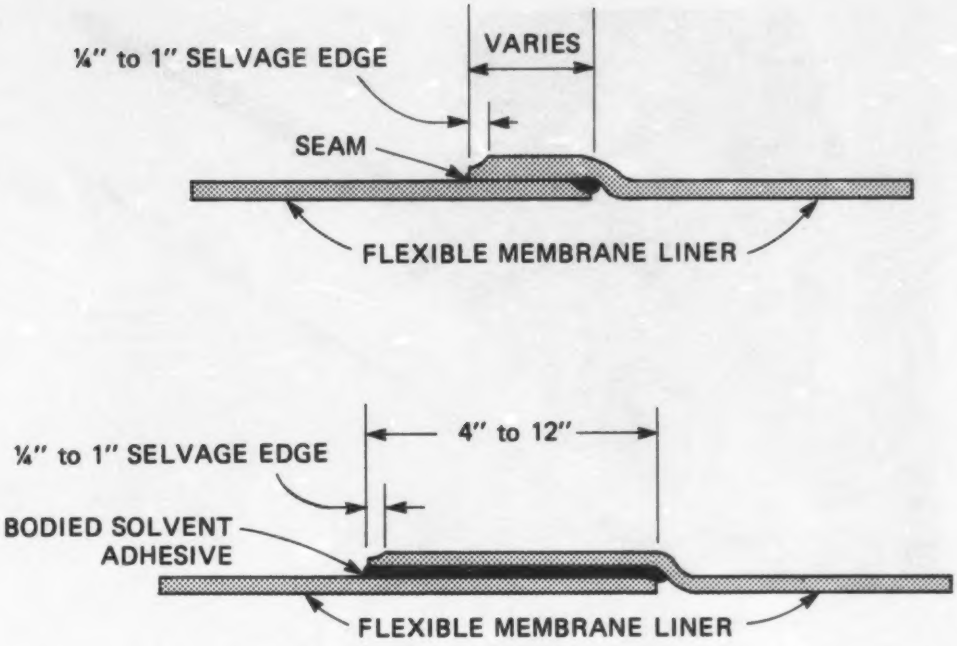


Figure IV-15 Typical factory seam (above) and field seam lap jointed. (From Small, 1980).

underneath the liner and the overlap is sufficient, then the top liner material should be peeled back and the surface prepared for the adhesive (Fig. IV-16). In the case of some liner materials, e.g. EPDM and CSPE, a surface cure must be removed with a solvent wash prior to seaming. Field crews should have suitable gloves to prevent skin reactions from the solvents (Figure IV-17). Respirators and eye protection may also be required. Once the surface cure has been removed, the adhesive can be applied to the liner material. Figure IV-18 shows the application of both a solvent and a contact adhesive. Generally, with a bodied solvent adhesive, the two surfaces should be placed together immediately and rolled with a steel or plastic roller perpendicular to the edge of the panel (Figure IV-19). Contact adhesive systems require that a certain tackiness be achieved before the two surfaces are placed together.

The crew should be careful not to allow any wrinkles to occur in the seam (Figure IV-20). All surfaces should be flat and rolled. It is important, whatever adhesive system is used, that the adhesive be applied uniformly. Field seaming should normally begin at the center of a panel and continue to each end of the seam. This minimizes large wrinkles which could occur if seaming began at one end or the other. In all cases, the adhesive system to be used by the field seaming crew should be that recommended by the manufacturer or a suitable substitute approved for a specific job.

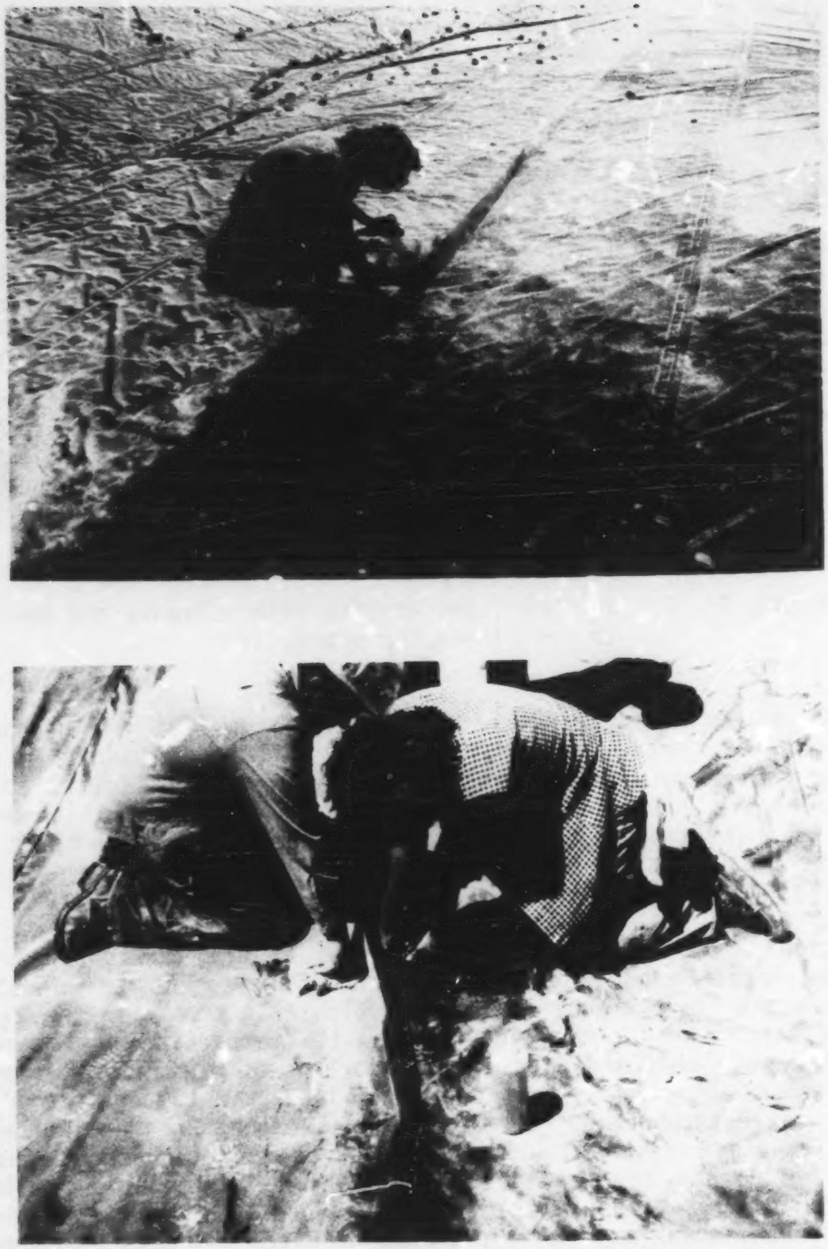


Figure IV-16. The surfaces to be seamed must be cleaned to remove dirt. Cleaning is usually accomplished with a solvent.

Figure IV-17. Seaming crews working with solvents are advised to use gloves for protection.

Generally, panels are placed so that field seams will run perpendicular to the toe of the slopes; that is, the seams will run up and down rather than along the side slopes. The reinforced materials can be placed so that seams run horizontally on side slopes. However, a good rule of thumb is always to place seams vertically on side slopes where possible without decreasing panel size or increasing field seaming. This practice minimizes stress on uncured field seams.

Installation of liner materials and field seaming during adverse weather conditions require special considerations with respect to adhesive systems and temperature limitations. This is particularly true with the thermoplastic materials since their properties change with temperature. Temperature also affects the rate that solvents will evaporate and the rate that seams become strong. Most adhesive systems work best when the temperature of the liner material itself is above 60°F. When ambient temperatures are below 60°F and a solvent adhesive system is being used, heat guns can provide an effective means to help bring the temperature of the liner material up to ideal conditions. Extreme caution must be exercised when using heat guns around flammable solvents, which may ignite, and chlorinated solvents which may generate the toxic gas, phosgene.

Cold weather seaming requires that the field crew exercise caution when making seams to assure that the temperature of the liner material reaches minimum acceptable conditions. A cold weather contact adhesive is sometimes used. Field seaming during precipitation should be avoided.

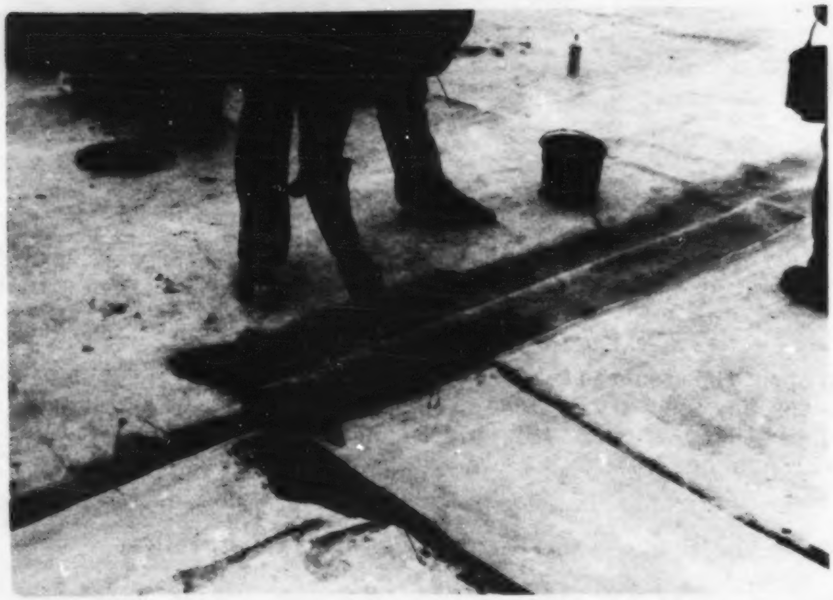


Figure IV-18. Field seaming. Adhesives are applied to the liner materials.

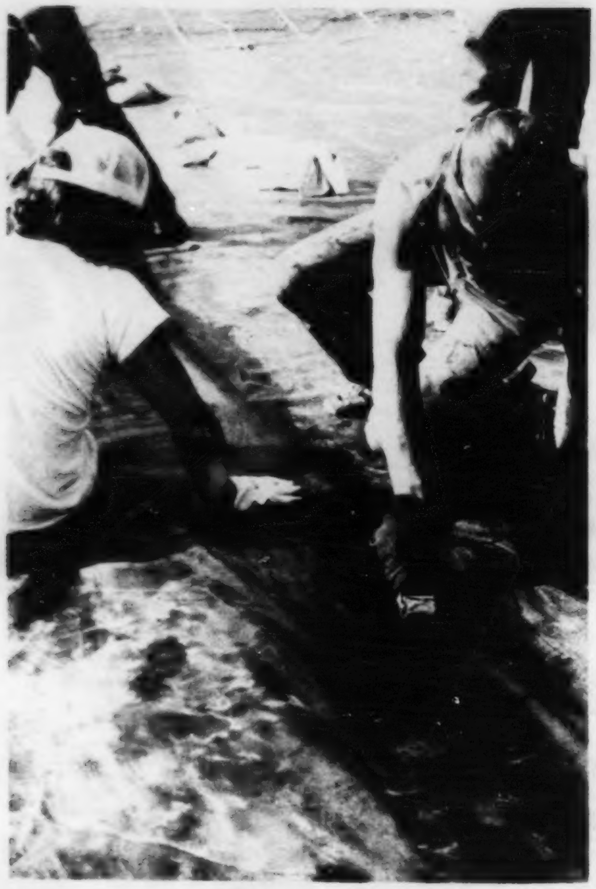
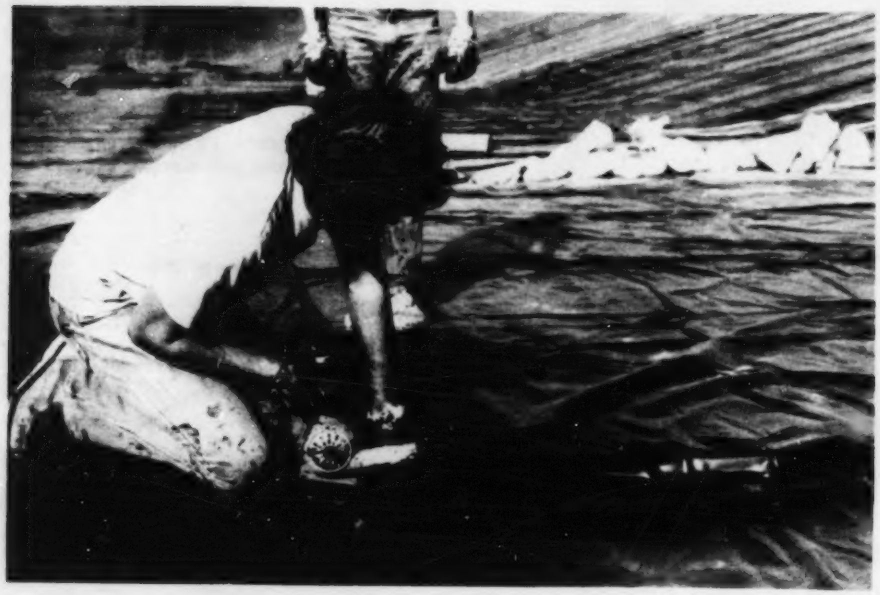


Figure IV-19. Rolling the seam. After the proper adhesive has been applied, the seam is rolled smooth.

Depending upon the location and the weather conditions, the number of panels placed in one day should not exceed the number which can be seamed in one day. This assures that, should bad weather conditions occur overnight, unseamed panels will not be left on the subgrade, subject to damage, especially from wind.

IV.6 Anchoring/Sealing Around Structures/Penetrations

Proper anchoring of the liner around the impoundment perimeter as well as conscientious tailoring and sealing of the liner around penetrating structures are essential to satisfactory liner performance. Generally, in cut-and-fill type impoundments, the liner material is anchored at the top of the dike or berm one of two ways: (1) using the trench-and-backfill method (Figure IV-21), or (2) anchoring to a concrete structure. The trench-and-backfill method seems to be recommended most often by liner manufacturers, probably due



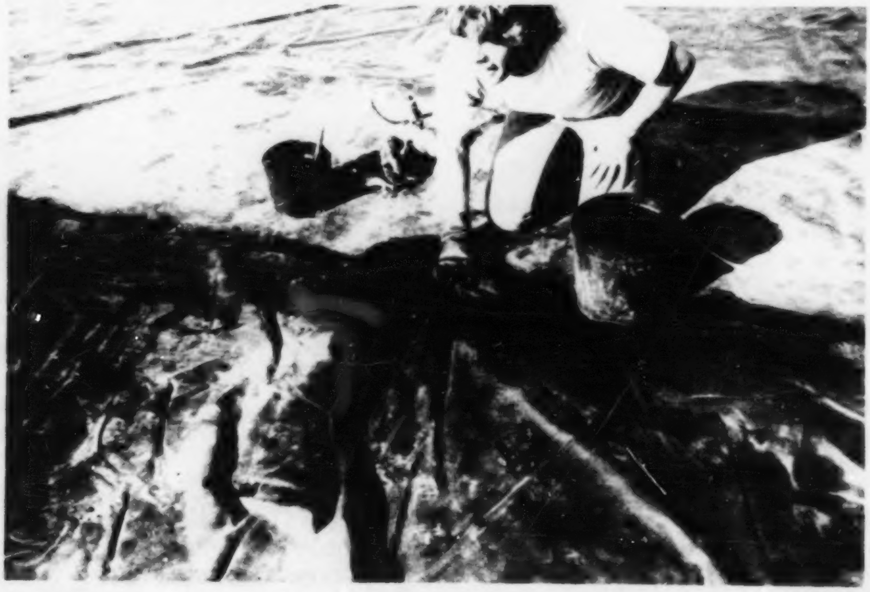


Figure IV-20. Repairing a wrinkle at the seams. The wrinkle is first preheated with a heat gun (top); after applying adhesive, the wrinkle is folded; the wrinkle has been rolled smooth and washed with a solvent; a patch is applied as a final step (bottom).

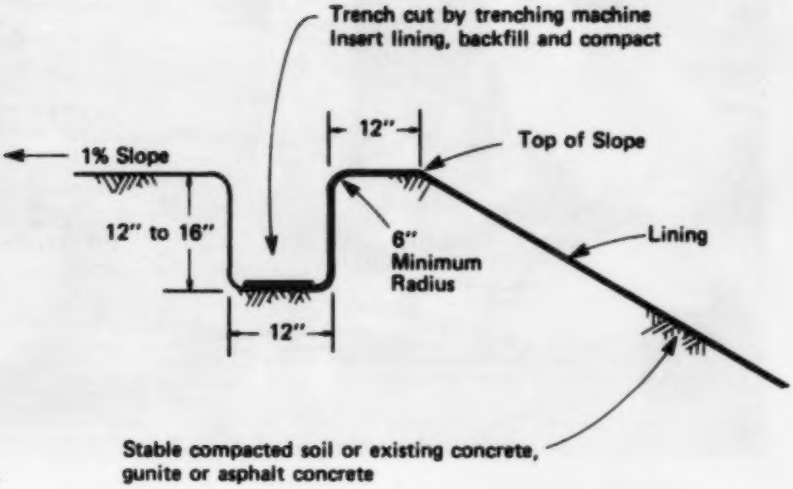

Trench cut by trenching machine
Insert lining, backfill and compact
1% Slope
12"
Top of Slope
12" to 16"
6"
Minimum
Radius
Lining
12"
Stable compacted soil or existing concrete,
gunite or asphalt concrete

Figure IV-21. Trench and backfill design for anchoring the perimeter of a membrane liner at the top of the pond sidewalls (Kays, 1977).

to its simplicity and economy. Excavation of the anchor trench in preparation for laying the liner is usually accomplished with a trenching machine such as a ditch witch or by using the blade of a bulldozer tilted at an angle. The latter method is considered to be less desirable. Dirt from the excavation should be spread away from the pit and smoothed to facilitate unrolling and spotting of panels.

Before opening and spotting the panels, provisions should be made for temporarily securing the edges of the liner panels in the anchor trench while the seaming takes place. After the seaming crew has completed the seams for a particular panel, the trench is backfilled with earth that was excavated from the trench. The trench should not be backfilled until after the panels have been seamed so that panels can be aligned and stretched, if necessary, for wrinkle-free seaming. If the trench (and the edge of the liner) is to be capped with concrete curbing, it is desirable to position reinforcing rods vertically in the trench prior to backfilling. These reinforcing rods serve to hold the liner in place while the seaming is done.

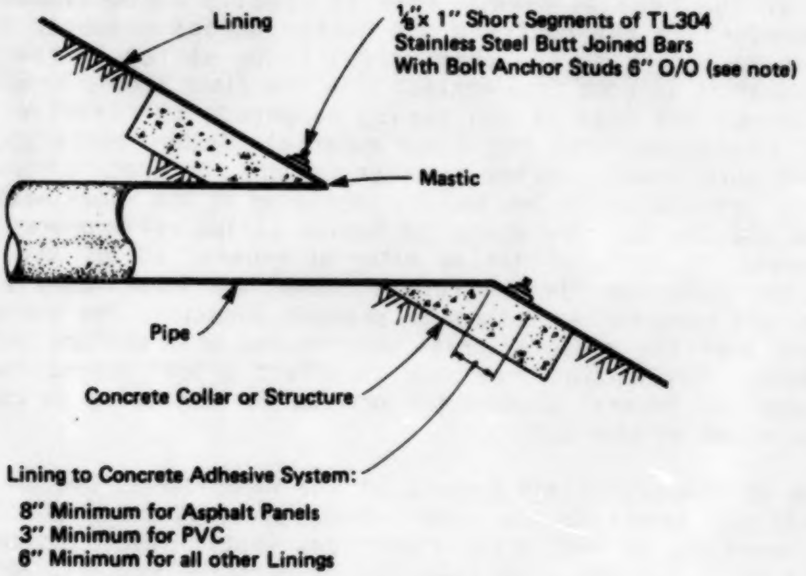
The perimeter of the liner may also be anchored to a concrete structure along the top of the berm or dike. This is usually accomplished with anchor bolts embedded in the concrete and batten strips composed of a material resistant to attack by the chemical(s) to be stored in the impoundment. Concrete that is to come into contact with the liner should have rounded edges and be smooth and free of all curing compounds to minimize abrasion and chemical interaction with the liner material. Anchor bolts should be positioned not more than 12 inches apart on centers. Concrete adhesive is applied in a strip (minimum width 3-6 inches, depending on the liner material) between the liner and the concrete where the batten strips will compress the liner to the concrete. A strip of lining material (chafer strip) may be sandwiched between the liner and the concrete wherever the liner material contacts an angle in the concrete structure to prevent abrasion. The batten strips are positioned over the liner material and secured with washers and nuts to the anchor bolts. Mastic should be used to effect a seal around the edge of the liner material. Several alternative methods for anchoring to concrete structures are shown in Kays (1977).

Depending on the design and purpose of the impoundment, one or more types of structures may penetrate the liner. These penetrations could include inlet, outlet, overflow, or mud drain pipes; gas vents; level indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations may occur in the bottom or through one of the sidewalls, depending upon their function. Because tailoring and sealing the liner around structures can be difficult and offers a possibility for failure of the liner, several manufacturers recommend that over-the-liner pipe placement be used wherever possible. This design facilitates future repairs or maintenance to the piping system.

When penetrations through the liner are necessary, most manufacturers recommend specific materials and procedures to be used to establish an effective seal around the various types of penetrations. Proper design of the penetrations and selection of an adhesive material that is compatible with the liner are important factors to be considered relative to expected liner performance. For instance, some liner materials are not easily sealed to concrete. Selection of alternative materials may be required. Other materials, on the other hand, may offer optimal conditions for obtaining a good seal; for example, PVC liner can be effectively sealed to PVC pipe using the appropriate solvent to meld the materials together.

Most manufacturers offer standardized engineering designs for (a) seals made in the plane of the liner, and (b) boots to be used around penetrations. If inlet or outlet pipes are introduced into the impoundment through a concrete structure, the seal can be made in the plane of the liner. An example of this type of seal is presented in Figure IV-22. Here again, a special liner-to-concrete adhesive system is used that is designed for each liner material. Anchor bolts embedded in the concrete and batten strips of stainless steel should be used to secure the liner to the concrete. Mastic should be used around the edges of the liner material to effect a complete seal.

Typically, specialized features such as pipe boots or shrouds are fabricated at the manufacturing facility to design specifications, although they can sometimes be prepared in the field by experienced personnel. Where reinforced

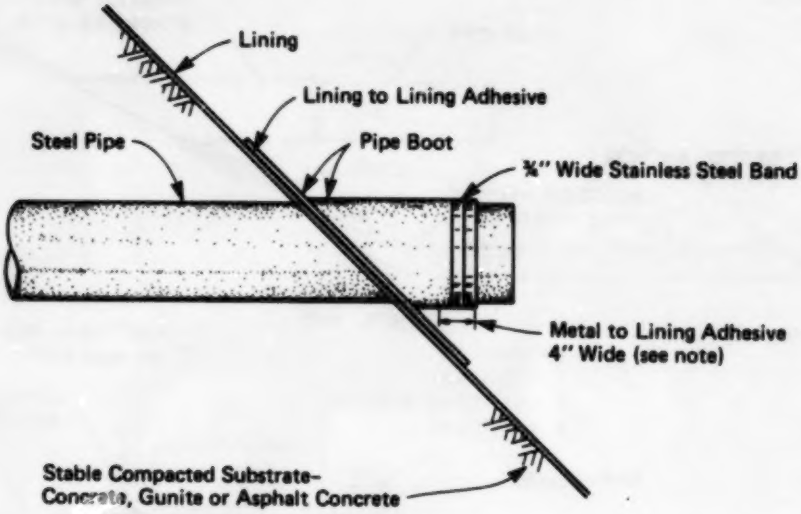

Lining
⅛" x 1" Short Segments of TL304
Stainless Steel Butt Joined Bars
With Bolt Anchor Studs 6" O/O (see note)
Mastic
Pipe
Concrete Collar or Structure
Lining to Concrete Adhesive System:
8" Minimum for Asphalt Panels
3" Minimum for PVC
6" Minimum for all other Linings

NOTE:
For asphalt panel linings, percussion driven studs thru 2" min. diameter x 1/16" thick galvanized metal discs at 6" O/C encased in mastic may be substituted for anchor shown

Figure IV-22. A commonly used flange type seal around penetrations (Kays, 1977).

membrane liners are being installed, manufacturers sometimes recommend that boots be constructed of unreinforced liner of the same type as that being installed. This allows the slightly undersized boot to be stretched over the appurtenance to assure good physical contact and allows some expandability in case the adjacent liner stretches due to settling. The boot is slipped over the pipe after the main piece of the liner has been cut and fitted around the base of the pipe. The proper adhesive is applied between the pipe and boot and a stainless steel band is placed around the boot where the adhesive has been applied between the pipe and boot. The base of the boot is seamed to the main part of the liner using the same adhesive system and methods used to make the field seams. Boots should be checked prior to installation to insure that the angle of intersection with the base is consistent with the angle created between the pipe and subgrade. An example of a seal created through the use of a pipe boot is presented in Figure IV-23.

It is important to assure that no "bridging" occurs in the liner material where angles are formed by the subgrade. Bridging is the condition that exists when the liner extends from one side of an angle to the other, leaving


Lining
Lining to Lining Adhesive
Steel Pipe
Pipe Boot
¾" Wide Stainless Steel Band
Metal to Lining Adhesive
4" Wide (see note)
Stable Compacted Substrate–
Concrete, Gunite or Asphalt Concrete

NOTE:
Clean pipe thoroughly at area of adhesive application

Figure IV-23. An example of a technique for sealing around penetrations using the boot type method (Kays, 1977).

a void beneath the liner at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the bottom of the impoundment. Particular attention should be directed to keeping the liner in contact with the subgrade at these locations and that it be in a relaxed condition. It is also important to be sure that compaction of the subgrade in these areas meets design specifications to avoid localized stressing of the liner material or seams.

Special considerations must be given to instances where dynamic head is going to be dissipated onto the liner. This would occur, for example, at an inlet structure where water will be flowing into the impoundment. Generally, a splash pad should be constructed by placing one or more additional layers of liner at the point of impact to help absorb energy resulting from the inflow of water. A concrete pad or a filter fabric geotextile may also be used under the liner to insure further mechanical stability (Figure IV-24). If water is to be discharged into an impoundment, often the design will specify a sluice type trough which can also be constructed out of liner material and placed on top of the main liner (Figure IV-25). This will help prevent

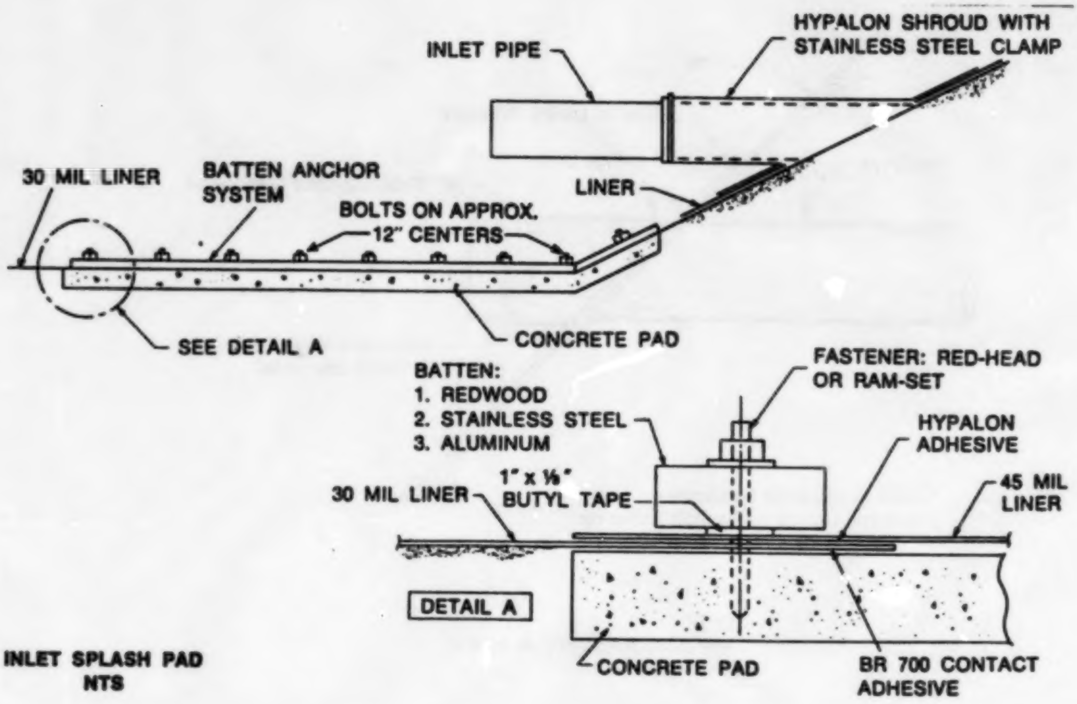

HYPALON SHROUD WITH STAINLESS STEEL CLAMP
INLET PIPE
30 MIL LINER
BATTEN ANCHOR SYSTEM
LINER
BOLTS ON APPROX. 12" CENTERS
SEE DETAIL A
CONCRETE PAD
BATTEN:
1. REDWOOD
2. STAINLESS STEEL
3. ALUMINUM
FASTENER: RED-HEAD OR RAM-SET
HYPALON ADHESIVE
1" x ⅛" BUTYL TAPE
30 MIL LINER
45 MIL LINER
DETAIL A
INLET SPLASH PAD
NTS
CONCRETE PAD
BR 700 CONTACT ADHESIVE

Figure IV-24. Splash pad construction using a concrete subbase. (Source: Burke Rubber Company)

damage to the main liner resulting from any abrasive material which might be present in the water discharged into the facility.

If gases are expected to accumulate under the liner or large expanses of the sides of an impoundment will be exposed to high velocity winds, gas vents should be installed. Gas vents should be located just below the berm on the fire board area.

If an aeration system is part of the facility design, appropriate precautions should be taken to insure that the liner surrounding the structure remains in position. This is usually accomplished by using a mooring pad placed on top of the liner for a floating aerator. The mooring pad also prevents mechanical damage to the liner immediately adjacent to the aerator. It is recommended that an additional layer of liner material be placed between the mooring pad and the main part of the liner. When a fixed aerator is used, the liner material may cover the foundation pad and an additional pad can be poured over the liner. Here again, an additional layer of liner material is sandwiched between the pad and liner. Permanent anchors should be placed ten feet apart in a circle approximately 20 feet from the base of the aerator to prevent the liner material from being lifted from the subgrade. Figure IV-26 shows some typical design details for aeration structures.

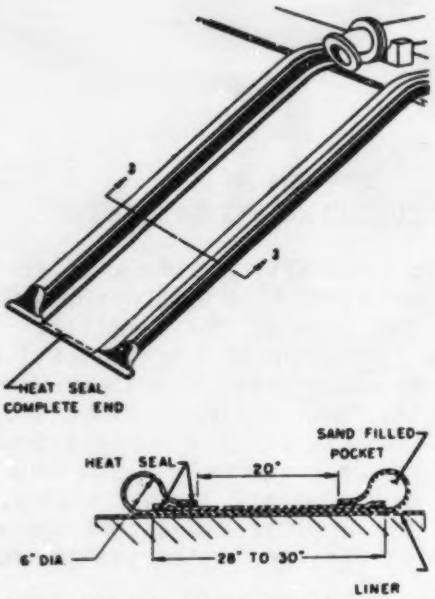

3
3
HEAT SEAL
COMPLETE END
SAND FILLED
POCKET
HEAT SEAL
20"
6" DIA
28" TO 30"
LINER

Figure IV-25. Sluice type trough constructed of liner material. The easiest method of placing inlet and outlet pipes into a membrane lined lagoon is over the top of the berms, using a protective liner to contain the discharge, thus protecting the main liner. The fewer protrusions that are designed into a lining, the easier it is to install and maintain both the liner and the piping. A double layer of liner material over the liner at the inlet may also be sufficient, as opposed to the prefabricated trough illustrated (Source: B. F. Goodrich).

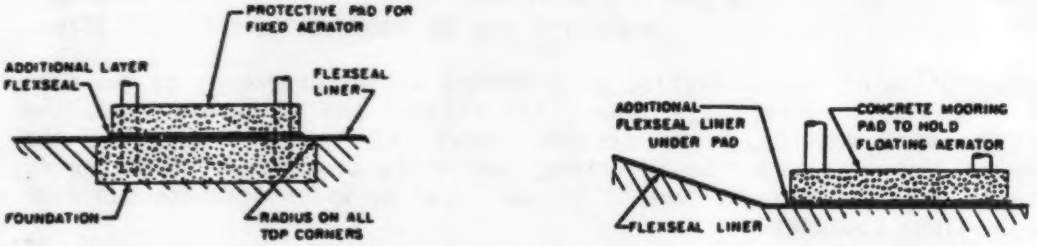

PROTECTIVE PAD FOR
FIXED AERATOR
ADDITIONAL LAYER
FLEXSEAL
FLEXSEAL
LINER
FOUNDATION
RADIUS ON ALL
TOP CORNERS
ADDITIONAL
FLEXSEAL LINER
UNDER PAD
CONCRETE MOORING
PAD TO HOLD
FLOATING AERATOR
FLEXSEAL LINER

Figure IV-26. Typical design details for floating and fixed aeration systems (Kays, 1977).

Personnel reviewing the design or performing quality control functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the material's use and installation. This includes everything from the liner's compatibility with the material being stored to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

Note: See Chapter 5 for References.

APPENDIX V
LEACHATE COLLECTION SYSTEM NETWORK

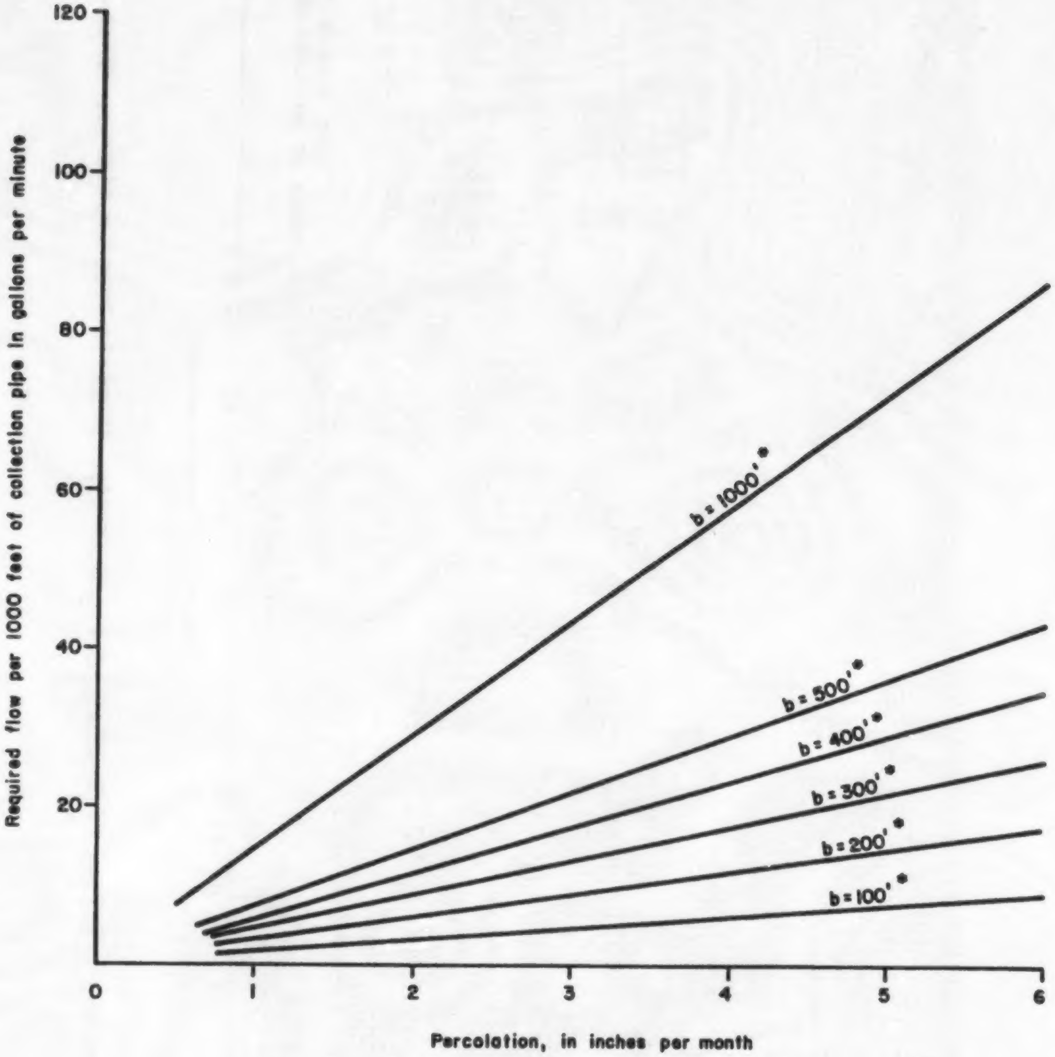
A leachate collection system generally consists of strategically placed perforated drain pipe bedded and backfilled with drain rock. The pipe can be installed in a trench or on the base of the landfill. The system can be installed either around the perimeter of the landfill or underneath the landfill in the form of a complex network of collection pipes. The latter is utilized when the areas involved are very large and/or the allowable head build up is small (see Section 5.6.3, "Transmissivity"). The collection system is drained to a sump or a series of sumps from which the leachate is withdrawn. This Appendix discusses the layout, sizing, installation, and selection of pipe material for leachate collection systems. A series of charts and tables are presented for use in the design and analysis of such systems.

V.1 Flow Capacity

As indicated in Chapter 5, the spacing of leachate collection pipes will influence the maximum head of leachate on the base of the fill, given a uniform rate of leachate percolation to a saturated fill and the permeability of the medium through which the leachate is withdrawn. Figure 5-26 can be used to select the required pipe spacing given an allowable leachate head over the base of the landfill. Figure V-1 shows the flow that must be carried in a collection pipe for various percolation rates and collection pipe spacings. With the required flow known, Figure V-2 can be used to select pipe sizes.

The configuration of the collection pipe network varies depending on the head allowed over the landfill base liner: the greater the allowable head, the greater the pipe spacing. For maximum control of lateral migration, the leachate collection system should extend completely around the perimeter of the site to provide absolute control of the level to which leachate can rise on this critical boundary.

An interior grid system becomes necessary if the leachate head on the base of the fill must not exceed a specified value. The slopes and spacing of the interior grid pipes are controlled largely by a base slope of a minimum of one percent. Placement of a layer of permeable material over the base of the fill, coupled with the use of an interior collection pipe grid, may be necessary in extreme cases where the development of a leachate head cannot be tolerated.



*Where b = width of area contributing to leachate collection pipe

Figure V-1. Required capacity of leachate collection pipe (Source: Emcon Associates).

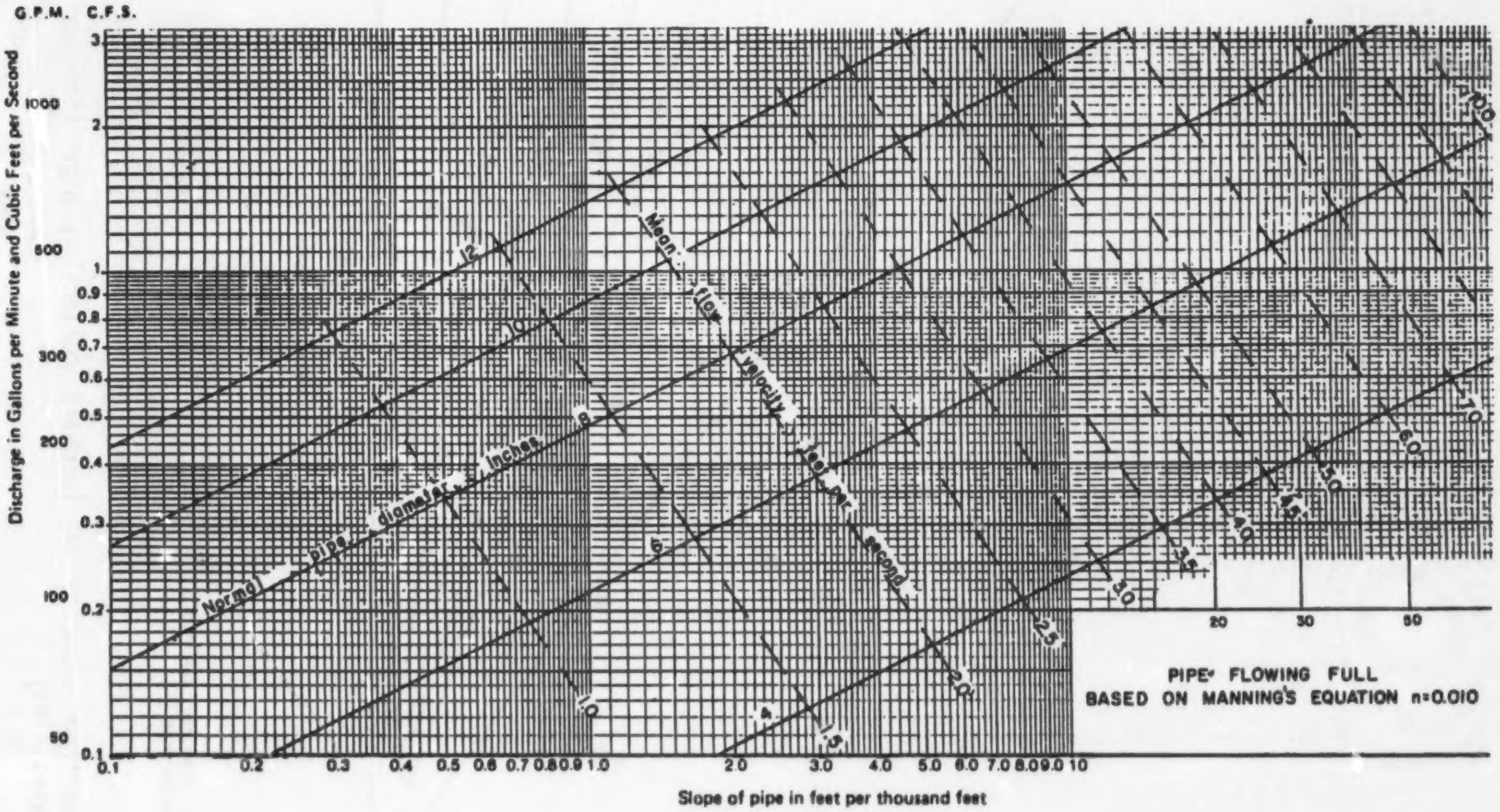


Figure V-2. Sizing of leachate collection pipe (Plastic Pipe Institute, 1975).

V.2 Structural Stability of Pipe

V.2.1 Introduction

Pipes installed at the base of a landfill to collect and conduct leachate to withdrawal wells can be subjected to high loading of waste fills, which can rise several hundred feet above the pipe.

Leachate collection pipes beneath landfills generally are installed in one of two conditions: (1) a trench condition or (2) a positive projecting condition. These installation conditions are shown on Figure V-3. In the analysis of the structural stability of a pipe under the imposed loading, the pipe is considered either a rigid or flexible conduit. Examples of rigid conduits are concrete and cast iron pipe. Plastic and fiberglass pipes are examples of flexible pipe. Because the landfill environment is highly corrosive, pipe materials generally selected for use in leachate control systems are plastic or fiberglass due to their relatively inert properties with respect to typical municipal leachate. This section discusses the structural stability of flexible pipe in landfill applications.

V.2.2 Loads Acting on Pipe

Loads are determined for one of two conditions: a trench condition or a positive projecting condition.

V.2.2.1 Trench Condition (Figure V-3)

This condition is assumed to exist whenever the top of the pipe is located below the ground surface. Load on the pipe is caused by both the waste fill and the trench backfill. These two components of the total vertical pressure on the pipe are computed separately and then added to obtain the total vertical pressure acting on the top of the pipe. The refuse fill is assumed to develop a uniform surcharge pressure, q_f, at the base of the refuse. The magnitude of q_f is given by the expression:

$$q_f = (\omega_f)(H_f)$$

where:

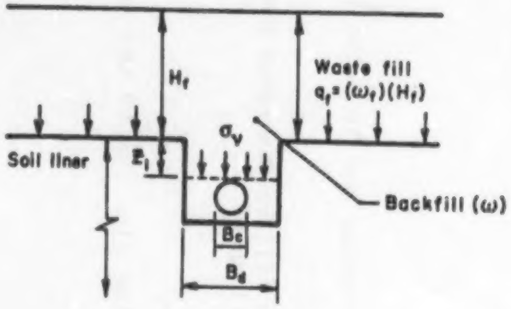
q_f = vertical pressure at the base of the refuse due to waste fill (lbs/sq ft)

ω_f = unit weight of the waste fill (lb g/cu ft); values range between 45 and 65 for municipal waste with soil cover

H_f = height of waste fill (ft).

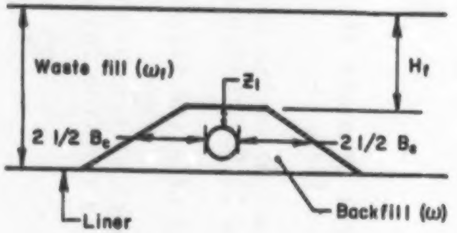
The value of the vertical pressure at the top of the pipe due to the waste fill may be determined from the following equation:

$$\sigma_{v_1} = q_f \, C_{\mu s}$$



H_f
Waste fill
$q_f = (\omega_f)(H_f)$
σ_v
Soil liner
Z_1
Backfill (ω)
B_c
B_d

a) TRENCH CONDITION



Waste fill (ω_f)
Z_1
H_f
2 1/2 B_c
2 1/2 B_c
Liner
Backfill (ω)

b) PROJECTING CONDITION

Equations for determining the vertical pressure acting on the pipe:

For TRENCH CONDITION:

$$\sigma_v = B_d \omega C_D + q_f C_{u.s.}$$

Where: $C_D = \dfrac{\left[1 - e^{-2K\mu(Z/B_d)}\right]}{2K\mu}$

$$C_{u.s.} = e^{-2K\mu(Z/B_d)}$$

$$W = \sigma_v B_c$$

For PROJECTING CONDITION:

$$\sigma_v = (\omega_f)(H_f) + \omega Z_1$$

DEFINITIONS:

ω = unit weight of backfill
W_f = unit weight of waste fill
H_f = height of waste fill
q_f = vertical pressure at the bottom of the waste fill
σ_v = vertical pressure at the top of the pipe
W = force per unit length of pipe
Z_1 = height of backfill above the pipe
B_d = width of trench
B_c = outside diameter of pipe
K = lateral pressure coefficient of backfill
μ = coefficient of friction between backfill and the walls

Figure V-3. Pipe installation - conditions and loading (Clarke, 1968).

The term $C_{\mu s}$, a load coefficient, is a function of the ratio of the depth of the trench, Z, (measured from the ground surface to the top of the pipe) to the width of the trench, B_d, and of the friction between the backfill and the sides of the trench. It may be calculated from the following equation or obtained from Figure V-4.

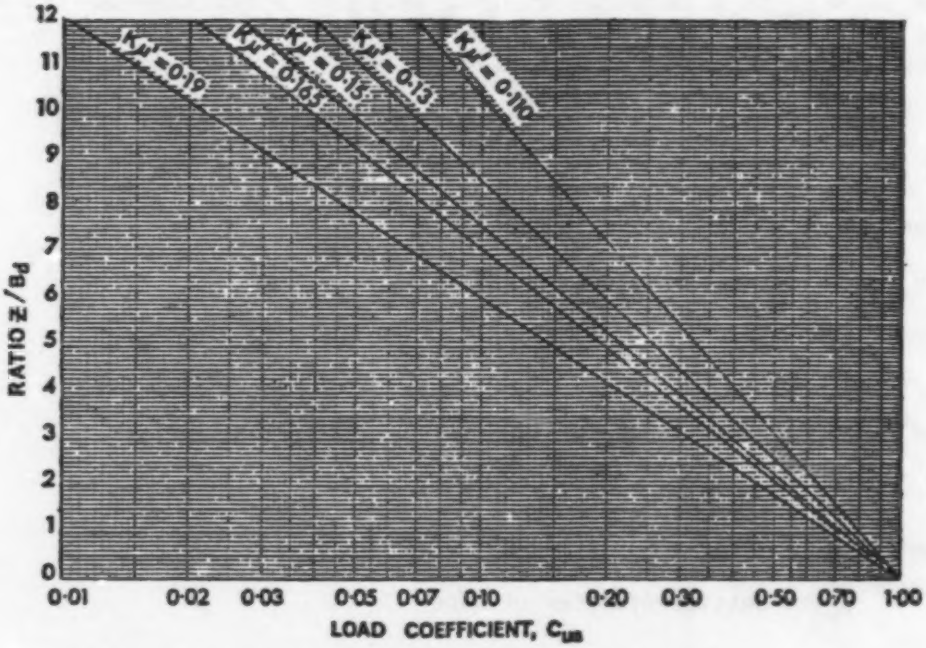
$$C_{\mu s} = e^{-2K\mu'(Z/B_d)}$$

where: K = lateral pressure coefficient of the trench backfill.

μ' = coefficient of friction between backfill and the walls of the trench.

Z = depth of trench from original ground surface to top of pipe (ft)

B_d = width of trench at top of pipe (ft).



Values of load coefficient C_{us} (trench uniform surcharge)

Figure V-4. Projecting condition - pipe load coefficient (Clarke, 1968).

The product of $K\mu'$ is characteristic for a given combination of backfills in natural (in place) soil. Maximum values for typical soils are presented in ASCE Manual of Practice, No. 37. Those values of $K\mu'$ representing soils in which flexible pipes are likely to be installed are:

Type of soil	Maximum value of $K\mu'$
Sand and gravel	0.165
Saturated top soil	0.150
Clay	0.130
Saturated Clay	0.110

The value of the vertical pressure at the top of the pipe due to the trench backfill may be determined from the following equation developed by Marston:

$$\sigma_{v_2} = (B_d)(\omega)(C_d)$$

where: ω = unit weight of trench backfill (lbs/cu ft).

The term C_d is a load coefficient which is a function of the ratio Z/B_d and the friction between the backfill and sides of the trench. It may be computed from the following equation or obtained from Figure V-5.

$$C_d = \frac{1-e^{-2K\mu'(Z/B_d)}}{2K\mu'}$$

where the terms are as defined above.

The total vertical pressure is equal to:

$$\sigma_v = \sigma_{v_1} + \sigma_{v_2} = q_f\ C_{\mu s} + B_d\ \omega\ C_d.$$

The force per unit length of the pipe is equal to:

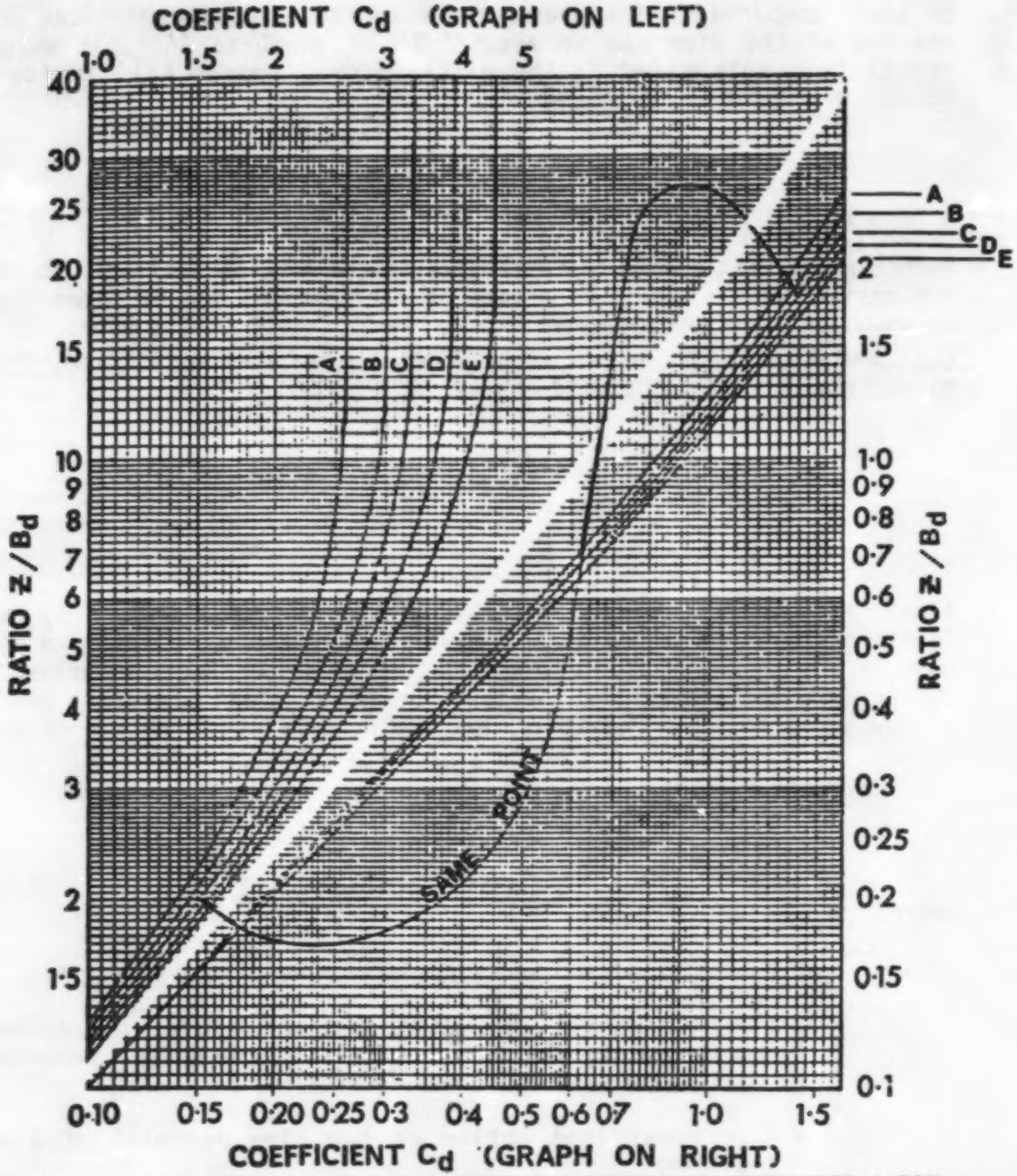
$$W = \sigma_v\ B_c$$

where: W = force per unit length of pipe

B_c = outside diameter of pipe

V.2.2.2 Positive Projecting Condition (Figure V-3)

This condition is assumed to exist whenever the top of the pipe is at or above the level of the refuse base. In this case, the load on the pipe can be assumed to be equal to the weight of a prism of overlying waste fill with a width B_c and height H_f plus the weight of a similar prism of gravel backfill above the pipe; because the pressure due to the gravel backfill typically will



A—C_d for $K\mu' = 0.19$, for granular materials without cohesion

B—C_d for $K\mu' = 0.165$ max. for sand and gravel

C—C_d for $K\mu' = 0.150$ max. for saturated top soil

D—C_d for $K\mu' = 0.130$ ordinary max. for clay

E—C_d for $K\mu' = 0.110$ max. for saturated clay

Values of load coefficient C_d (back fill)

Figure V-5. Trench Condition - Pipe Load Coefficient (Clarke, 1968).

be small compared to the pressure due to the fill, the vertical pressure on the top of the pipe can be assumed to be equal to the unit weight of the refuse fill multiplied by the distance from top of fill to top of pipe, thus:

$$\sigma_v = (\omega_f)(H_f).$$

V.2.2.3 Perforated Pipe

Perforations will reduce the effective length of pipe available to carry loads and resist deflection. The effect of perforations can be taken into account by using an increased load per nominal unit length of the pipe. If l_p equals the cumulative length in inches of perforations per foot of pipe, the increased vertical stress to be used equals:

$$(\sigma_v)_{design} = \frac{12}{12-l_p} \times (\sigma_v)_{actual}$$

V.2.3 Deflection

A well accepted formula for calculating flexible pipe deflection under earth loading is that developed by Spangler. This equation, also known as the Iowa formula, is presented together with suggested values for its various constants in the 1970 edition of the American Society of Civil Engineers (ASCE) Manual of Practice, No. 37, Chapter 9, Section E, Subsection 1, and is as follows:

$$\Delta y = D_e \frac{KWr^3}{EI + 0.061\, E'r^3}$$

where:

Δy = horizontal and vertical deflection of the pipe (in)

D_e = a factor, generally taken at a conservative value of 1.5, compensating for the lag or time dependent behavior of the soil/pipe systems (dimensionless)

W = vertical load acting on the pipe per unit of pipe length (lb/in)

r = mean radius of the pipe (in)

E = modulus of elasticity of the pipe materials (psi)

E' = modulus of passive soil resistance (psi) (normally estimated to be 300 psi for soils of Proctor density of 65%, and 700 psi for soils of Proctor density of at least 90%)

K = bedding constant, reflecting the support the pipe receives from the bottom of the trench (dimensionless) (a conservative value generally taken 0.10)

I = moment of inertia of pipe wall per unit of length (in^4/in); for any round pipe, $I = t^3/12$ where t is the average thickness (in).

The equation can be rewritten to express pipe deflection as a decimal fraction of the pipe diameter, B_c, and to relate it to the vertical stress on the pipe as follows:

$$\frac{W}{B_c} = \sigma_v = \left(\frac{\Delta y}{B_c}\right)\left(\frac{EI + 0.061E'r^3}{D_e K r^3}\right).$$

Solutions to this equation are shown graphically in Fig. V-6 where the quantity $\sigma v/(\Delta y/B_c)$ has been plotted against the passive soil modulus E'. The relationship between $\sigma v/(\Delta y/B_c)$ and E' has been shown for four plastic pipes: 4 and 6-inch Schedule 40 and 4 and 6-inch Schedule 80 PVC pipe. In computing the quantity EI for these pipes, a reduced modulus was used to account for creep of the plastic pipe. A value equal to 142,000 psi was used to correspond to the modulus at 50 years under sustained loading (see Janson, 1974). Also shown is the relationship for EI=0. This would represent a relationship between $\sigma v/(\Delta y/B_c)$ and E' if the stiffness of the pipe is neglected.

In addition to using the chart to check the adequacy of a given pipe, the chart can be used to determine the necessary value of EI/r^3 which the pipe must have for given values of $\sigma max/(\Delta y/B_c)$ and E'. Although it is customary to use either 300 or 700 psi for the value of the modulus of passive soil resistance, it should be noted that the modulus of elasticity of a coarse grained soil (sand or gravel) increases with increasing pressure (or depth in the ground). Thus, it should be expected that the modulus of passive soil resistance also would increase with increasing pressure or depth of fill.

The term EI in Spangler's equation reflects the pipe's contribution to the total resistance to deflection under load offered by the pipe/soil system. This term, known as the pipe's Stiffness Factor, is related to the pipe's behavior under parallel plate loading as per ASTM D 2412, External Loading Properties of Plastic Pipe by Parallel Plate Loading, by the following expression:

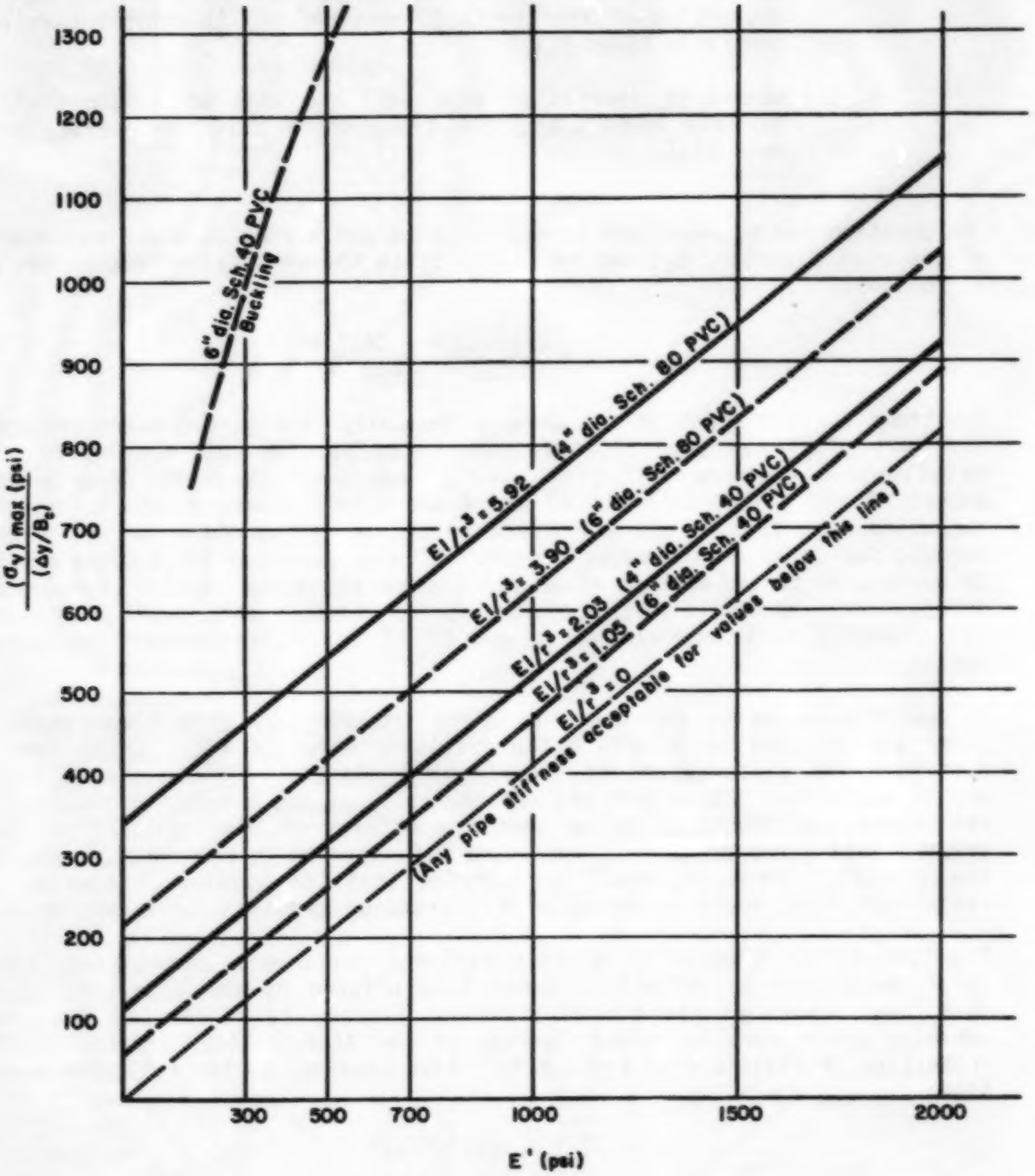
$$EI = 0.149r^3(F/\Delta y)$$

where:

E, I and r are as previously defined

F = the recorded load (lb/linear inch) required to produce a pipe deflection Δy

Δy = the pipe's deflection (in).



$$\frac{\sigma_y}{(\Delta y/B_c)} = \frac{\left[EI + 0.061\ E' r^3\right]^*}{D_e K r^3} \qquad \text{Assumed: } \left.\begin{matrix} D_e = 1.5 \\ K = 0.1 \end{matrix}\right|^*$$

Figure V-6. Selection of Pipe Strength
* (ASCE, 1969)

Minimum values of the term $F/\Delta y$, called Pipe Stiffness, are set according to Pipe DR (dimension ratio) by the ASTM PVC Sewer Pipe Specifications D 3033 and D 3034. The DR represents the ratio of the pipe's average outside diameter to its minimum wall thickness. Thus, for each DR there is a corresponding minimum specified value of $F/\Delta y$.

The above expression for EI can be substituted into the previous equation for deflection to obtain the following:

$$\frac{\sigma_v}{(\Delta y/B_c)} = \frac{(0.149F/\Delta y) + 0.061E'}{D_e K}$$

Solutions to this equation can be made on a graph similar to Fig. V-6 where the quantity $\sigma_v/(\Delta y/B_c)$ is plotted against the soil modulus E' for several values of $F/\Delta y$.

V.2.4 Buckling Capacity

The capacity of a buried plastic drain pipe to support vertical stresses may be limited by buckling. Estimates of the vertical stresses at which buckling of the 6-inch Schedule 40 PVC pipe (the most flexible of the four pipes shown) will occur are indicated by the curve in Fig. V-6. For the four pipes shown, buckling would not be a controlling factor. However, it could be a controlling factor, depending on the flexibility of the pipe and the modulus of passive soil resistance. Specific information for other sizes and pipe materials proposed for use in the collection system should be secured from the pipe manufacturer.

V.2.5 Compressive Strength

The capacity of the pipe to support vertical stresses may be influenced by the circumferential compressive strength of the pipe. The designer or reviewer should secure up-to-date information on circumferential compressive strength characteristics from the manufacturer of the type of pipe proposed for use.

V.2.6 Construction Loadings

A pipe correctly designed to withstand loading from a high fill can fail from loading received during construction. Although only a fraction of a stationary wheel or tracked vehicle load applied at the ground surface over a trench is transmitted to a pipe through the trench backfill, the percentage increases rapidly as the vertical distance between the loaded surface and the top of the pipe decreases. In addition, moving loads cause impact loading generally considered to have a 1.5 to 2.0 multiplier effect over stationary loading.

In general, equipment should not cross leachate collection drains installed in trenches with shallow cover or in projecting installations. When equipment must be routed across a drain, impact loading can be minimized by mounding material over the pipe to provide a vertical separation of 4 feet between the loaded surface and the top of the pipe.

V.2.7 Procedures for Selection of Pipe Strength

The procedures used to select the proper strength pipe are illustrated in the following examples:

Trench Installation (See Figures V-4 and V-7)

Given: $Z = 1'\text{-}8''$ $\quad H_f = 100$ feet waste fill

$B_d = 1'\text{-}6''$ $\quad \omega_f = 50$ pcf

$K_\mu' = 0.19$ $\quad \omega = 110$ pcf

pipe diameter = 4"

Determine: Required pipe strength/schedule.

Step 1 - Determine the maximum vertical pressure σ_v (psf) acting on the top of the pipe.

$$\frac{Z}{B_d} = \frac{1.67}{1.5} = 1.11 \qquad q_f = (\omega_f)H_f = 100\ (50) = 5000 \text{ psf}$$

from Fig. V-4, $C_{\mu s} = 0.64$

Fig. V-5, $C_d = 0.9$

then; $\sigma_v = (\omega)(B_d)(C_d) + (q_f)(C_{\mu s})$

$= (110)(1.5)(0.9) + (5000)(0.64)$

$= 3348 \text{ psf} = 23.3 \text{ psi} = J_v \text{ max}$

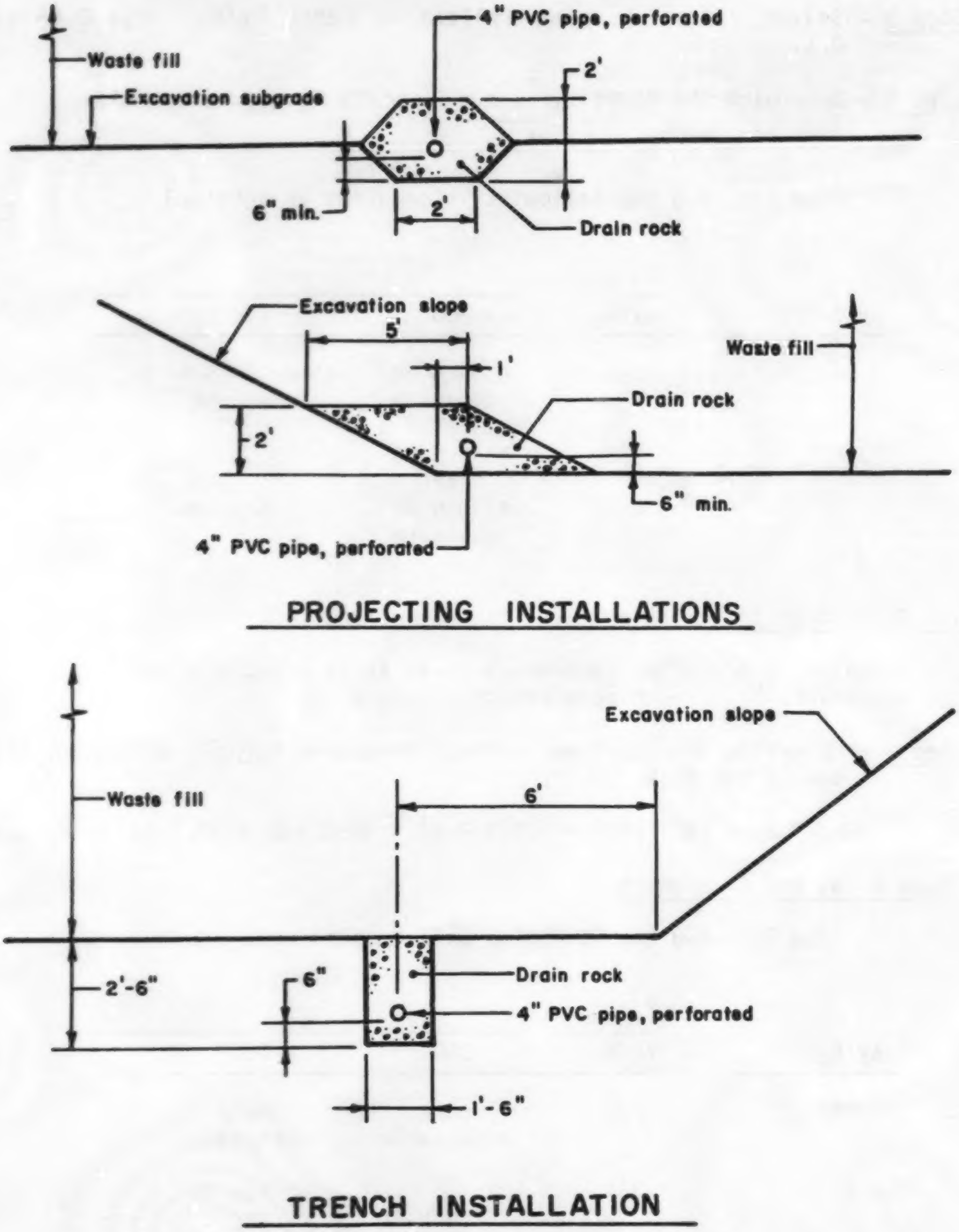

4" PVC pipe, perforated
Waste fill
Excavation subgrade
2'
6" min.
2'
Drain rock
Excavation slope
5'
1'
Waste fill
Drain rock
2'
6" min.
4" PVC pipe, perforated
PROJECTING INSTALLATIONS
Excavation slope
Waste fill
6'
2'-6"
6"
Drain rock
4" PVC pipe, perforated
1'-6"
TRENCH INSTALLATION

Figure V-7 Typical Leachate Collection Drains (Source: Emcon Associates)

Step 2 - Select the appropriate modulus of passive soil resistance E' (psi). For gravel bedding use 300 to 700 psi.

Step 3 - Select allowable pipe deflection ratio $\Delta y/B_c$. Use 0.05 to 0.1.

Step 4 - Determine the quantity $\frac{\sigma_{v\ max}}{\Delta y/B_c}$, where $\sigma_{v\ max}$ is in psi.

From Fig. V-6 the following information is obtained.

$\Delta y/B_c$	$\frac{\sigma_{v\ max}}{\Delta y/B_c}$	E'	
		300	700
0.05	466	4" Sch 80 adequate	4" or 6" Sch 80 adequate
0.1	233	4" Sch 40 or 6" Sch 80 adequate	Any pipe

Positive Projecting Installation (See Figures V-3 and V-7)

Given: Z, = 6"; other parameters given as in example above
Determine: Required pipe strength/schedule

Step 1 - Determine the maximum vertical pressure σ_v(psf) acting on the top of the pipe.

$$\sigma_v = \omega_f H_f + \omega Z_1 = (50)(100) + (110)(0.5) = 5055 \text{ psf} = 35.1 \text{ psi} = J_{v\ max}$$

Steps 2, 3, and 4 as above

From Fig. V-6 the following will be obtained.

$\Delta y/B_c$	$\frac{\sigma_{v\ max}}{\Delta y/B_c}$	E'	
		300	700
0.05	702	none acceptable	none acceptable
0.1	351	4" Sch 80 adequate	4" Sch 40 or 6" Sch 80 adequate

Note: See Chapter 5 for References.

APPENDIX VI

SWELL BEHAVIOR OF SOILS AND CLAYS

Nayak and Christensen (1971) enumerated eight factors which affect the swell behavior of a soil. A ninth factor which appears to be relevant in the case of liners has been added. These nine are:

1. Type and amount of clay mineral.
2. Initial placement conditions e.g. structure, density.
3. Stress history.
4. Nature of pore fluid.
5. Temperature.
6. Volume change permitted during swelling pressure measurements.
7. Shape, size, and thickness of the sample.
8. Time.
9. Load conditions.

Nayak and Christensen, testing a limited number of samples but covering a wide spectrum of physical and mineralogical properties, produced a semiempirical relationship in which the swell is predictable if the plasticity index (PI), percent clay content (C), and moisture content of the sample (w) are known. The swelling potential (Sp) for a mixture of sand-grundite-bentonite, is:

$$Sp = (1.3548 \times 10^{-2}) \times (PI)^{1.59} \times \frac{C}{w} + 4.8046$$

and for a mixture of sand-kaolinite-bentonite is:

$$Sp = (4.4938 \times 10^{-3}) \times (PI)^{1.74} \times \frac{C}{w} + 14.722$$

Although the use of these kinds of relations is encouraged, one has to be aware of their limitations. In this particular case, for instance, the regression equations were calculated using very high swell data, presumably because of the use of a Na-bentonite. Naturally occurring soils are quite different.

When different specimens of a silty clay soil were compacted at various combinations of density and moisture content, it was found that, for samples with the same density just prior to testing for a change of volume, both shrinkage and swell increased with a decrease in moisture content during compaction (Seed and Chan, 1959). Consequently, if volume changes are to be prevented, the compaction operation in the field has to be conducted at the highest operationally possible moisture content (Holtz and Gibbs, 1956). The higher the moisture content and the lower the density as compacted, the safer the above conclusion since, in this range, errors in the moisture content will result in only slight increases in swell. However, soil liners cannot be compacted at low densities for other obvious reasons. One should bear in mind that the higher the density as compacted for the same air-filled porosity, the larger the underestimation of swell if a certain error is made in the moisture content of the soil during compaction.

Plotting isoswell curves on a density-moisture content graph, (Figure VI-1), Holtz and Gibbs (1956) were able to show that (Seed et al., 1962):

a. An increase in molding water content at any given density causes a decrease in swelling pressure and swell.

b. An increase in density at low moisture content causes an increase in swell. An increase in density at high moisture content does not alter drastically the swell characteristics.

The character of an isoswell map on a density-moisture content graph depends, for any particular soil, on the relative proportion of solid, liquid, and air phases. Thus, the extreme cases, "maximum swell" and "no swell at all", should correspond, respectively, to the situations "high solid-low liquid-low air" and "low solid-high liquid-high air". Different situations can be integrated by the values of the negative pore-water pressures for the as-compacted state.

The structural characteristics of the soil cannot be overlooked; indeed, the value of the pore water pressure measured in a compacted clayey soil has to reflect, to a large extent, structural differences. As was pointed out by Seed et al. (1960), the differences in structure generated on the dry-side-of-optimum, due to the different methods of compaction, have a minimal effect upon shrink-swell characteristics. The same is not true on the wet side; the statically compacted soil (with a more flocculated structure) swells more than the sample compacted with a kneading compactor. Day (1955) showed a decrease in soil suction upon shear (when, presumably, the soil particles were in a less flocculated state) in comparison to the situation "at rest" when the particles tended to have a more flocculated arrangement. Consequently, the statically compacted samples swell more because their flocculated structure corresponds to lower pore-water pressure, i.e. larger affinities for water.

In the situation relating to clayey soil liners, the volume change tendencies of the compacted soil liner are relevant only to the extent that they affect flow properties, if soil strength does not have to be considered. It was

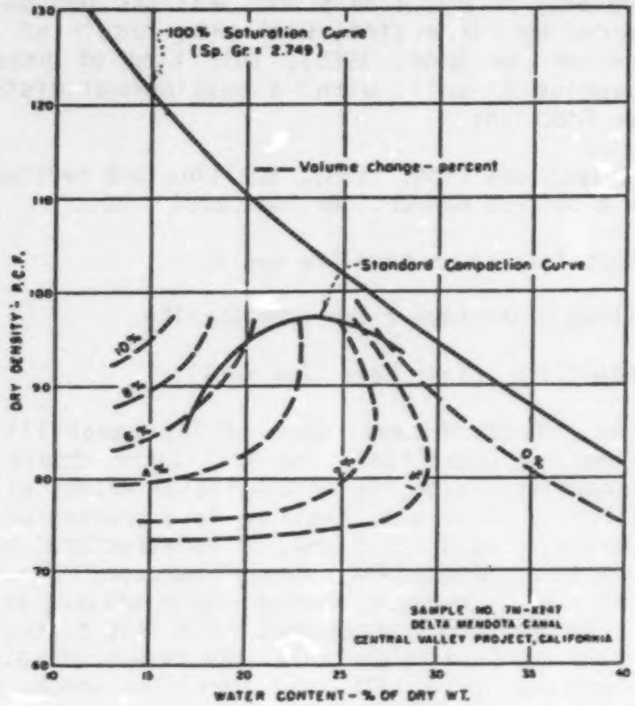


Figure VI-1 Isoswell lines on moisture-density graph; expansive clays under extremely dry and dense conditions (Seed et al., 1962).

recognized some time ago that shrink-swell tendencies are important in the case in which an "hydraulic" structure such as a soil liner is constructed (Holtz and Gibbs, 1956).

One of the most often quoted examples in which swell characteristics were related to flow properties is the one described by Macey (Lutz and Kemper, 1959) in which, for the particular soil used, the ratio $K_{water}/K_{nonpolar\text{-}organic}$ was in the range 10^{-5} to 10^{-6}. This small ratio was attributed to the swelling of the soil when water was the fluid used, compared to the rigid-structure behavior in the case in which nonpolar organic solution was the flowing fluid. In most practical situations, the effect would be less drastic.

In general, it is assumed that swelling is beneficial rather than detrimental, in the sense that swelling reduces the average pore size (McNeal and Coleman, 1966; Shainberg et al., 1971) and enhances dispersion and, associated with this, plugging of pores (Hardcastle and Mitchell, 1974; Shainberg et. al., 1971). It is also possible that a reduction of permeability upon swelling and dispersion is associated with an alteration in properties of the water in the vicinity of the matrix wall (Miller and Low, 1963). Situations were described when the pore size distribution of the soil was such that internal soil erosion was favored by dispersion, with the result of an increase in permeability (Aitchison and Wood, 1965); this kind of behavior should be considered an exception in soils with a quasinormal distribution of different particle size fractions.

As Cardwell stated (Mielenz and King, 1955), swelling and sealing ability of clays do not match in a perfect manner. He indicated that:

a. All high permeability clays have low swell.

b. All high swelling clays have a low permeability.

c. Some low permeability clays have low swell.

Since, at present, the effect of swell upon soil permeability (although tending to reduce) cannot be quantified, the soil liner should be designed for a particular permeability, assuming no beneficial effect will occur due to saturation and swelling. After all, swelling is a process of bulk volume increase, i.e. an increase in void ratio and, if no structural changes occur during water uptake, then the permeability should increase. The basic reason why this almost never happens is because, during water uptake, soil capillary forces are partially released which corresponds to a less flocculated structure. The net bulk volume increase is partially the result of water uptake by the fines between relatively large silt soil particles which, by this mechanism, are pushed farther away from each other.

In assessing the volume change tendencies of a soil which will be compacted into a soil liner, thixotropic characteristics have to be identified, if present. Thixotropy is considered to be the most important mechanism which generates sensitive structures in soils having sensitivity values up to eight (Mitchell, 1976). Sensitivity is defined as the ratio of the strength of undisturbed soils to that of the soil remolded. Thixotropic hardening, associated with a decrease in pore water pressure as a result of a more flocculated structure, is defined as the increase in strength with time at constant volume, temperature, and water content. Since changes in structure due to thixotropic hardening result in a more flocculated structure, one could predict that when a thixotropic clayey soil is compacted into a soil liner with a characteristic permeability, in time this value will increase.

Bentonites, which are popular in the area of water management, are highly thixotropic materials; they harden to gel in short times (Boyes, 1972). The Na-montmorillonite, typically the main component of the bentonite rock, is responsible for this behavior. In general, montmorillonitic clays, widely recognized as perfect soils for water confinement operations because of their very small particle sizes, swelling, and sealing characteristics, etc., have to be looked upon as being potentially troublesome materials; for this kind of soils, short-term laboratory experiments cannot predict the long-term field behavior. As an example of such behavior, Kelley observed the failure of a bentonite pond floor which cracked during operation, although it was permanently submerged under water (Mielenz and King, 1955).

According to Mielenz and King (1955), materials with free swell larger than 600% should be used if an impermeable liner has to be obtained. While this figure is quite large, it emphasizes the generally found trend that swelling soils are sealing soils. It seems to us that due to the paucity in quantitative information regarding the volume change-permeability relationship, rather than counting on the beneficial effect of swell, the designing unit should make sure that the presence of a swelling soil will not be the cause of an unwanted behavior.

Note: For references, see Chapter 3.

APPENDIX VII

SYSTEM ANALYSIS AND OPTIMIZATION OF SOIL LINER DESIGN

The purpose of the design is to achieve a seepage below the liner, lower than a certain critical value, q_p. The analysis of the system can be done using different procedures. As an example, we will use the McWhorter and Nelson (1979) analysis. For convenience, we will preserve the nomenclature used by the authors. A schematic representation of the flow system is presented in Figure VII-1.

In the subsequent analysis, it is assumed that the geometry of the system is unchanged in time, i.e. the depth of the free waste fluid, y, the depth of the solid waste, D_t, and the depth of the underlying undisturbed soil, D_f, are given. The depth of the soil liner D_l is variable. The permeability of the solid waste, K_t, and the permeability of the isotropic, homogeneous underlying soil K_f are also given. The permeability of the soil liner K_l is variable and can be optimized vis-a-vis the depth of the soil liner D_l to result in a seepage rate lower than q_p. Other parameters which will be found in the analysis have the following meaning:

n = soil porosity, equal to volumetric moisture content when the soil is saturated.

θ_i = initial volumetric moisture content of the underlying soil.

h_d, θ_r, and λ = parameters experimentally found when determining the moisture characteristic curve (MCC). The MCC is the relation between the magnitude of suction applied and the equilibrium moisture content corresponding to the given negative head.

h_d = displacement pressure or air-entry pressure (negative). The threshold suction needed to break soil capillaries and allow water drainage. For most soils it is between -50 cm and -150 cm. The more clayey a soil the lower (the more negative) the h_d value.

θ_r = the residual moisture content on a MCC, the quasi-steady moisture-content encountered at large suctions. Often, to obtain this moisture content, the pressure has to be decreased to -15 atmospheres. θ_r is roughly the water stored in submicronic pores. It is normally in the range of 0.05 - 0.20 with the high values corresponding to clayey soils.

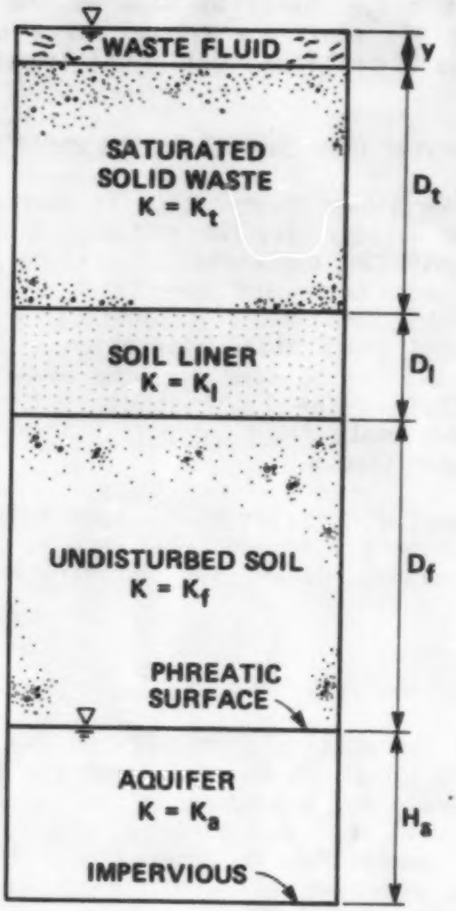

WASTE FLUID
y
SATURATED SOLID WASTE
K = K$_t$
D$_t$
SOIL LINER
K = K$_l$
D$_l$
UNDISTURBED SOIL
K = K$_f$
D$_f$
PHREATIC SURFACE
AQUIFER
K = K$_a$
H$_a$
IMPERVIOUS

Figure VII-1. Sketch of the flow system.

λ = a shape factor of the MCC. In the present analysis, it was assumed equal to unity.

h_c = effective capillary drive = $h_d \frac{(2+3\lambda)}{(1+3\lambda)}$. Since $\lambda = 1$ in this analysis, $h_c = 1.25\ h_d$.

The flow event is visualized as occurring in three stages:

Stage 1 - The infiltration of the fluid into the underlying, originally unsaturated soil. In the wetted region the same soil may or may not be fully saturated.

Stage 2 - This stage starts as soon as the wetting front reaches the groundwater or its capillary fringe and a groundwater mound is being formed. Stage 2 continues until the mound reaches the base of the liner.

Stage 3 - Saturated flow throughout the whole system.

It is clear that the slower every stage is developed the better suited the system is to confine wastes. If, for instance, Stage 3 is reached the success of the system in controling contamination will rely heavily on the ability of different strata (soil liner and underlying soil) to chemically bind the contaminants. If fresh waste fluid is continually added to the waste disposal site, the strata will reach their saturation. In the long run the system sketched in Figure VII-1 will have the same composition and concentration as the fresh waste fluid. The limiting concentration at a well will be a fraction of the fresh waste fluid concentration due to dilution by the incoming fresh groundwater stream.

At the present level of knowledge, we have to prevent the occurrence of Stage 3 and even Stage 2. Accordingly, we will analyze numerically some of the important parameters during the infiltration towards the groundwater (Stage 1).

Example of Numerical Analysis for Stage 1

The advancement of the wetting front between the soil liner/underlying soil interface and the original groundwater level can occur either as a saturated or as an unsaturated flow, depending on the geometry and flow properties of the traversed strata. For our purpose, the less saturated the flow the better, since the seepage rate is proportional to the degree of saturation. Consequently, it is important to design the system in such a way as to promote unsaturated flow during infiltration.

The flux across the sequence of solid waste-soil liner is given by the equation:

$$q = \frac{(y + D_t + D_l) - h_f}{\frac{D_t}{K_t} + \frac{D_l}{K_l}} \qquad (1)$$

where h_f is the pore-water pressure in the wetted underlying soil during flow with all other terms already defined (Equation 10, McWhorter and Nelson, 1979).

For unsaturated flow to occur, h_f has to be more negative than the air-entry pressure, h_d, i.e. $h_f < h_d$. Combining this condition with Equation 1 and $q=K_f$ results in: (Equation 14 in McWhorter and Nelson, 1979).

$$y + D_t + D_l - K_f \left[\frac{D_t}{K_t} + \frac{D_l}{K_l}\right] < h_d. \qquad (2)$$

Assuming the optimization of the system can be achieved by varying D_l and K_l, the depth and the permeability of the soil liner, and assuming the permeability of the underlying soil k_f is equal to 10^{-5} cm sec^{-1} and its air-entry pore-water pressure, h_d, is equal to -50 cm equivalent water, equation 2 becomes:

$$y + D_t - 10^{-5} \frac{(D_t)}{(K_t)} + 50 < 10^{-5} \frac{(D_l)}{(K_l)} - D_l \qquad (3)$$

The values of the left hand side of the inequality expressed in cm, are presented in Table VII-1 for different y, D_t, and K_t levels.

TABLE VII-1. LEFT HAND SIDE OF EQUATION 3, in cm

y, feet	D_t, feet	K_t (cm sec^{-1}) 10^{-4}	10^{-5}	10^{-6}
3	1	169	141	-133
	20	690	141	-5351
60	1	1906	1879	1604
	20	2428	1879	-3619

The right hand side of the inequality (Equation 3) expressed in cm, is presented in Table VII-2, for different combinations of k_l and D_l, the permeability and the depth of the soil liner.

TABLE VII-2. RIGHT HAND SIDE OF EQUATION 3, in cm.

K_l, cm sec^{-1}	D_l feet 1	6
10^{-6}	275	1,678
10^{-7}	3,023	18,123
10^{-8}	39,500	182,880

The condition of unsaturated flow $h_f<h_d$ is observed whenever the ratio of any figure from Table VII-1 to any figure from Table VII-2 is less than +1.

In Table VII-3, we present the system requirements which will generate the best observance of the condition $h_f<h_d$ and the worst observance of the same inequality.

TABLE VII-3. From Tables VII-1 and VII-2. THE BEST AND THE WORST COMBINATIONS OF PARAMETERS WHICH RESULT IN $h_f<<h_d$ AND $h_f>>h_d$, RESPECTIVELY

Parameters	Best Condition (Least Saturated Flow) $h_f<<h_d$	Worst Condition (Saturated Flow) $h_f>>h_d$
y, feet	3	60
D_t, feet	20	20
K_t, cm sec^{-1}	10^{-6}	10^{-4}
D_l, feet	6	1
K_l, cm sec^{-1}	10^{-8}	10^{-6}

The inspection of data in Tables VII-1, VII-2, and VII-3 should provide the designer with important clues regarding the choice of the relevant soil parameters D_l and K_l. Moreover, in the real situation the variability of the parameters, in the left part of the inequality, i.e. Equation 3, is much smaller than the one considered in this example. Consequently, the figures in Table VII-1 will be closer to each other and the choice of a proper combination of D_l and K_l will thus be facilitated.

As an example, let us assume that the calculation of the left hand side term in Equation 3 resulted in a value equal to 1500. In Table VII-2, we find that the combination D_l = six feet and $K_l = 10^{-6}$ cm sec^{-1} satisfies our requirements, since 1678 > 1500. The same requirements are satisfied by D_l = two feet and a permeability K_l = approximately 3×10^{-7} cm sec^{-1}. Considering both engineering and economic conditions, the designer will be able to optimize the two parameters.

Let us consider that the underlying soil has different properties than the ones assumed in the previous example. Suppose now $K_f = 10^{-6}$ cm sec^{-1} and $h_d = -150$ cm. This set of data should correspond to a more clayey soil. The new working equation generated for this case will be:

$$y + D_t - 10^{-6}\,\frac{(D_t)}{(K_t)} + 150 < 10^{-6}\,\frac{(D_l)}{(K_l)} - D_l \qquad (4)$$

Paralleling the previous example, the values of the left hand side of the inequality are presented in Table VII-4.

TABLE VII-4. LEFT HAND SIDE OF EQUATION 4, in cm

y feet	D_t feet	K_t (cm sec^{-1}) 10^{-4}	 10^{-5}	 10^{-6}
3	1	272	269	241
	20	845	790	241
60	1	2009	2006	1979
	20	2583	2528	1979

The right hand side of Equation 4 is presented in Table VII-5.

TABLE VII-5. RIGHT HAND SIDE OF EQUATION 4, in cm.

K_1 cm sec^{-1}	D_1 feet 1	 6
10^{-6}	0	0
10^{-7}	275	1,646
10^{-8}	3,020	18,107

The conclusion to be drawn from the first step of calculations is that unsaturated flow in the underlying soil is secured when the ratios K_1/K_f and K_t/K_f are very low. This can be seen from the inspection of Equation 2.

The condition of unsaturated flow $h_f<h_d$ is only the first step of the analysis. The result of this first step does not tell anything about the absolute value of the seepage through the system. To solve this aspect of the problem use is made of the relationship (Equation 16 from McWhorter and Nelson, 1979):

$$q = \frac{(y + D_t + D_1) - h_d\left[\frac{q}{K_f}\right]^{-1/(2+3\lambda)}}{\frac{D_t}{K_t} + \frac{D_1}{K_1}} \tag{5}$$

Before proceeding with the analysis the designer of the soil liner needs to know the q value (equivalent to q_p the permissible flux in the text, Section 5.2). Let us assume that the analysis of the system as a whole yielded a

q = 3 inches/year = 2.4×10^{-7} cm. sec^{-1}. Assuming, together with this figure, that the two important properties of the underlying soil are: $K_f = 10^{-5}$ cm sec^{-1} and h_d = -50 cm equivalent water, the resulting working equation becomes:

$$D_t \left(\frac{2.40 \times 10^{-7}}{K_t}\right) - y - D_t - 105.4 = D_1 - D_1 \left(\frac{2.4 \times 10^{-7}}{K_1}\right) \qquad (6)$$

The left hand side of Equation 6 can be calculated for different y, D_t, and K_t values. The results expressed in cm, are presented in Table VII-6.

TABLE VII-6. LEFT HAND SIDE OF EQUATION 6, in cm

y feet	D_t feet	K_t (cm sec^{-1}) 10^{-4}	10^{-5}	10^{-6}
3	1	-227	-227	-220
	20	-805	-792	-660
60	1	-1965	-1964	-1957
	20	-2542	-2529	-2398

The left hand side of Equation 6 and its right side have, for the chosen parameters, values between -200 and -2600 cm. If two particular values for the depth of the soil liner D_1 are considered, one foot and six feet, the needed permeabilities of the soil liner K_1 can be calculated. They are presented in Table VII-7.

TABLE VII-7. SOIL LINER PERMEABILITY K_1, REQUIRED TO RESTRICT THE FLUX AT q = 3"/YEAR, WHEN THE LEFT HAND SIDE OF EQUATION 6 TAKES VALUES BETWEEN -200 AND -2600. FOR TWO DEPTHS OF THE SOIL LINER, D_1.

Left hand side of Equation 6	D_1 feet 1	6
-200	3.2×10^{-8}	1.1×10^{-7}
-600	1.2×10^{-8}	5.6×10^{-8}
-1000	7.1×10^{-9}	3.7×10^{-8}
-1400	5.1×10^{-9}	2.8×10^{-8}
-1800	4.0×10^{-9}	2.2×10^{-8}
-2200	3.3×10^{-9}	1.8×10^{-8}
-2600	2.8×10^{-9}	1.6×10^{-8}

By comparing the figures from Tables VII-6 and VII-7, one should be able to decide about the particular soil liner permeability K_1 required. For this particular case, one can see that the choice will be quite difficult since it may be impractical to compact the soil to yield the low range of permeabilities indicated in Table VII-7.

The inspection of Equation 6 reveals that the required permeability is controlled by the magnitude of y and D_t. The term -105.4 in the left hand side of the equation is not very influential in determining the k_1 value. Not so, when y and D_t are relatively small. In this situation the term $[h_d(q/K_f)^{-1/(2+3\lambda)}]$ becomes quite significant. Table VII-8 presents the values of this term for different ranges of h_d, λ, K_f and q. The ranges chosen are deliberately broad to overemphasize the significance of each of the parameters.

TABLE VII-8. VALUES OF THE TERM $h_d \left[\frac{q}{K_f}\right]^{-1/2+3\lambda}$ FOR DIFFERENT VALUES OF h_d, λ, K_f and q.

q cm sec^{-1}	K_f cm sec^{-1}	h_d = -10 cm		h_d = -300 cm	
		λ = 0.5	λ = 5	λ = 0.5	λ = 5
10^{-6}	10^{-4}	-37	-13	-1118	-393
	10^{-6}	-10	-10	-300	-300
10^{-8}	10^{-4}	-139	-17	-4168	-516
	10^{-6}	-37	-13	-1118	-393

The values for q, i.e. the required limiting flux, and k_f, i.e. the saturated permeability of the underlying soil, should be known to the designer of the soil liner. Consequently, the designer should have no problems in deciding on the row of the table corresponding to the particular system. The choice of a particular column of Table VII-8 is a much more difficult step since it involves information regarding the moisture characteristic curve (MCC) of the underlying soil, h_d and λ. Since the MCC is not routinely determined in geotechnical laboratories we will not recommend that it be determined. On the other hand, some of the combinations between K_f, h_d, and λ are not possible. Thus, a soil with a permeability $K_f = 10^{-4}$ cm sec^{-1}, an air-entry pressure h_d = -300 and a λ = 0.5 probably does not occur in nature and the term in Table VII-8 will almost never be lower than -10^3. As we mentioned in the case in which the depth of the waste fluid, y, and that of the solid waste, D_t, are small, the relative significance of this term becomes important. Table VII-8 indicates that this is true the lower the ratio q/K_f.

Table VII-6 shows that, if the waste fluid plus the solid waste head is large (e.g. larger than 50 feet), the permeability of the undisturbed underlying soil becomes critical in generating a low permissible flux, since for this situation a deep soil liner of low permeability is required, and this situation may not be economical.

For the situation in which the condition of unsaturated flow is not observed, i.e. when $h_f \geq h_d$, the downward movement in the underlying soil will occur as saturated flow. According to McWhorter and Nelson (1979), such a situation will be observed, for instance, for the following set of data:

$y = 10$ feet

$D_t = 3$ feet

$D_l = 1$ foot

$K_t = 10^{-4}$ cm sec^{-1}

$K_l = 10^{-8}$ cm sec^{-1}

$K_f = 10^{-7}$ cm sec^{-1}

$h_d < 0$

Assuming $h_c = -50$ cm, the flux can be calculated using the equation (Equation 22 from McWhorter and Nelson, 1979):

$$q = K_f \frac{(L + y + D_t + D_l - h_c)}{(L + D_t \frac{K_f}{K_t} + D_l \frac{K_f}{K_l})} \tag{7}$$

The calculated flux below the soil liner when the wetting front is at a distance L equal to 10 m below the liner, will be 1.13×10^{-7} cm sec $^{-1}$.

If the soil porosity, n, is equal to 0.4 and the initial volumetric moisture content θ_i equal to 0.25, the relationship between time t and L can be expressed, using:

$$\frac{n-\theta_i}{K_f} \left[L + (D_t \frac{K_f}{K_t} + D_l \frac{K_f}{K_l} - y - D_t - D_l + h_c) \ln \left(\frac{L + y + D_t + D_l - h_c}{y + D_t + D_l - h_c}\right) \right] = t \tag{8}$$

For the set of data considered, the time t corresponding to L = 10 m is equal to 38.3 years. Since the flow was saturated and the volume occupied by the incoming waste effluent accounts for 15% of the soil bulk volume ($n - \theta_i = 0.15$), the length of the waste effluent column saturating the underlying soil is equal to 150 cm. The ratio of 150 cm over 38.3 years results in an average q equal to 1.24×10^{-7} cm sec^{-1}, which checks well with the figure calculated using Equation 7.

The presented numerical example has many limitations and the designer should be aware of them:

a. The real system to be analyzed may have variable dimensions in time, for instance if the incoming waste accumulates in the waste disposal site.

b. Flow properties of all traversed strata can be altered in time.

c. Some of the characteristics of the underlying soil (h_d and λ). which have been discussed in this presentation can be very sensitive to minute soil intrinsic property changes. Thus, an apparently homogeneous underlying soil can have, at different locations along the vertical flow direction, different h_d and λ values.

d. The temporary physico-chemical retention of the potential contaminants present in the original waste fluid has been disregarded in this analysis. Most of the experimental work on miscible displacement performed so far refers to saturated flow. In unsaturated condition, the processes of diffusion, hydrodynamic dispersion, adsorption, phase change of chemical species, etc., are expected to be connected in a more complex manner.

The most important merit of the presented analysis is that it considers the flow to be unsaturated which is a reality in the field, in most instances.

The analysis for design can be carried out using other procedures. If the system is more complicated than the one presented in our example, advantage can be gained by using a computer assisted numerical analysis.

Note: See Chapter 5 for references.

APPENDIX VIII

CASE STUDY ANALYSIS METHODOLOGY

This Appendix illustrates the case study method of analysis for developing project costs, and possibly other project components. Depending upon the type and size of project envisioned, the case study method can range from a fairly simple analysis to a very complex procedure. Our example case study is a straightforward and simple illustration of the technique.

Case Study of Community X for a Waste Impoundment

A site within Community X has been chosen as the location of a hazardous waste impoundment facility, which is to serve the surrounding metropolitan area containing several industrial concerns. The site is flat and the facility has the design criteria and parameters shown in Table VIII-1.

TABLE VIII-1. DESIGN CRITERIA AND PARAMETERS

Item	Criteria value
Flow	
Average design flow	60 gpm (4000 ft^3/day)
Pond	
Minimum requirement	120 acres
Cell size	15 acres
Number of cells	8
Total design area	120 acres
Pond depth	
Freeboard	2 feet
Minimum (for liquid seal)	1 foot
Storage	4 feet
Total design depth	7 feet
Embankments	
Slope	3:1
Top width (minimum)	8 feet
Liners	
Primary	45 mil reinforced CSPE
Secondary	30 mil reinforced CPE
Monitoring wells	10
Life	20 years

The engineer for the facility has determined that thin polymeric membrane liners are necessary to contain the wastes adequately. That decision was effected by the inadequacy of the native soil and the unavailability of a nearby suitable clayey soil for construction into a liner. The wastes to be impounded are not radioactive. The literature has revealed that the wastes to be impounded do not adversely affect the reinforced chlorosulfonated polyethylene liner nor do they adversely affect the chlorinated polyethylene liner. Compatiblity testing accomplished during the design phase had confirmed the above conclusion. The owner and the engineer have decided to use a double liner system with the following configuration. A 30 mil reinforced CPE liner (secondary liner) is placed over a graded compacted native soil. On top of the CPE liner is a three foot layer of moderately compacted native soil which contains the perforated pipe drain system. The perforated pipe trench is backfilled with filter sand or gravel. A thin soil layer is then placed over the three foot layer. A 45 mil reinforced CSPE is placed on top as the primary liner. The monitoring system consists of one well per cell located near the lowest point of the underdrain system plus two groundwater observation wells perforated in the native soil subgrade located down gradient of the impoundment.

Due to possible wave action in the impoundment facility during adverse weather conditions, two feet of freeboard is provided. Impoundment embankments are to be constructed with 3:1 slopes from material obtained near or on the site. To minimize erosion of these earthen embankments or dikes, a vegetative and/or rock cover may be utilized. A minimum top width of eight feet is required. Particulate emissions from impoundment areas will be minimized by maintaining solids in a slurry or liquid state. Total design depth of the pond is the sum of the required freeboard, the minimum storage depth necessary to maintain the contents in a liquid state, and the design storage depth. In order to maintain operation flexibility and maximize efficiency and effectiveness, the impoundment is divided into smaller cells. Each cell has an area of 15 acres. In case of leakage or maintenance operations, liquid wastes can be pumped to adjacent cells. The ability to drain individual cells provides flexibility in control of the liquid depth of a cell thereby increasing operation reliability.

Table VIII-2 presents the capital costs for the waste impoundment facility. Table VIII-3 shows the operating costs and Table VIII-4 presents the total annual costs of the facility.

TABLE VIII-2. CAPITAL COSTS FOR WASTE IMPOUNDMENT FACILITY

Component	Cost[a], thousands of dollars
Construction	
Excavation	630
Smoothing and clearing	114
Drainage and collection	165
Liner[b]	10,694
Monitoring system[c]	120
Subtotal	11,723
Impoundment closure	
Final cover	30
Revegetation	120
Monitoring	48
Subtotal	198
Construction contingencies	
Engineering, administrative, legal and permit costs (25%)	2,980
Total Impoundment Capital Cost	14,901

[a] Based on prices quotes from August, 1980.

[b] Primary liner and secondary liner plus installation. Based on $0.85/sq.ft. reinforced chlorosulfonated polyethylene and 0.70/sq. ft. CPE.

[c] Assume 10 wells.

TABLE VIII-3. OPERATING COSTS FOR IMPOUNDMENT FACILITY

Item	Annual cost $/yr	Unit cost $/1,000 gal
Impoundment		
Power	24,880	0.024
Operation and maintenance	116,120	0.11
Total	141,000	0.13

TABLE VIII-4. ANNUAL COSTS FOR IMPOUNDMENT FACILITY

Component	Annual costs
Capital costs[a]	$1,995,000
Operating costs	141,000
Total	$2,136,000

[a] Twenty year amoritization at 12 percent interest - capital recovery factor = 0.13388.

APPENDIX IX
SPECIFICATIONS FOR FLEXIBLE POLYMERIC MEMBRANE MATERIALS

The physical property values in the tables listed below are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information but should be used with discretion. These values are preliminary and subject to change.

These specification tables represent current opinion of the data points to characterize the membrane product as now on the market and are not proper for product performance or installation or engineering design criteria *per se*. For example, the low temperature resistance numbers represent qualities for a few minutes at a given temperature and must not be interpreted or extrapolated into installation temperature qualities or comparisons.

LIST OF PROPOSED NATIONAL SANITATION FOUNDATION STANDARDS FOR FLEXIBLE MEMBRANE LINERS FOR WASTE DISPOSAL FACILITIES

Polymer	Unsupported sheeting		Supported sheeting	
	Designation[a]	Variations[b]	Designation[a]	Variations[b]
Polyvinyl chloride (PVC)	1-A	3		
Chlorinated polyethlyene (CPE), thermoplastic	1-B	2	2-A	2
Butyl rubber (IIR)	1-C	3	-	-
Polychlorprene (Neoprene, CR)	1-D	3	-	-
High-density polyethylene (HDPE)	1-E	2	-	-
Ethylene propylene rubber (EPDM)	1-F	3	2-D	3
Epichlorohydrin rubber (ECO)	1-G	3	-	-
Chlorinated polyethylene (CPE), vulcanized	1-H	2	-	-
Elasticized polyolefin (ELPO)	1-I	1	-	-
Chlorosulfonated polyethylene (CSPE)	1-J	1	2-B	3
Thermoplastic nitrile PVC	-	-	2-C	3
Elasticized PVC	-	-	2-E	1

[a] Designation of specification by National Sanitation Foundation (NSF).
[b] Number of variations either in gage or in type of liner.

Source: Meeting of NSF Joint committee of Flexible Mebrane Liners, July 22-24, 1980.

TABLE 1A. MATERIAL PROPERTIES

UNSUPPORTED POLYVINYL CHLORIDE (PVC)

Property	Test Method	Gauge (nominal)		
		20	30	45
Thickness	ASTM D1593 Para 8.1.3	±5%	±5%	±5%
Specific Gravity (minimum)	ASTM D792 Method A	1.20	1.20	1.20
Minimum Tensile Properties (each direction)	ASTM D882			
1. Breaking Factor (pounds/inch width)	Method A or B (1 inch wide)	46	69	104
2. Elongation at Break (percent)	Method A or B	300	300	300
3. Modulus (force) at 100% Elongation (pounds/inch width)	Method A or B	18	27	40
Tear Resistance (pounds, minimum)	ASTM D1004	6	8	11
Low Temperature	ASTM D1790	-15°F	-20°F	-20°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	±5	±5	±5
Water Extraction	ASTM D1239 (as modified in Appendix A)	-.35% max.	-.35% max.	-.35% max.
Volatile Loss	ASTM D1203 Method A	0.7% max.	0.5% max.	0.4% max.
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)			
1. Breaking Factor		-5	-5	-5
2. Elongation at Break		-20	-20	-20
3. Modulus at 100% Elongation		±10	±10	±10
Bonded Seam Strength[2] (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	36.8	55.2	83.2
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A	60	82	100

---

[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1B. MATERIAL PROPERTIES

UNSUPPORTED CHLORINATED POLYETHYLENE (CPE)

Property	Test Method	Gauge (nominal)	
		20	30
Thickness	ASTM D1593 Para. 8.1.3	±5%	±5%
Specific Gravity (minimum)	ASTM D792 Method A	1.20	1.20
Minimum Tensile Properties (each direction)	ASTM D882		
1. Breaking Factor (pounds/inch width)	Method A or B	34	43
2. Elongation at Break (percent)	Method A or B	250	300
3. Modulus (force) at 100% elongation (pounds/inch width)	Method A or B	8	12
Tear Resistance (pounds, minimum)	ASTM D1004	3.5	4.5
Low Temperature	ASTM D1790	-20° F	-20°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	±18	±18
Water Extraction	ASTM D1239 (as modified in Appendix A)	-0.35% max.	-0.35% max.
Volatile Loss	ASTM D1203 Method A	0.7% max.	0.5% max.
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)		
1. Breaking Factor		-5	-5
2. Elongation at Break		-20	-20
3. Modulus at 100% Elongation		+10	+10
Bonded Seam Strength[2] (factory seam, breaking factor ppi width)	ASTM D3083 (as modified in Appendix A)	27	34
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A	75	100
Percent CPE Resin by Weight of total polymer	NSF verification[3]	>50	>50

---

[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

[3] NSF verification procedures described in Appendix ____.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1C. MATERIAL PROPERTIES

UNSUPPORTED BUTYL RUBBER

Property	Test Method	Gauge (nominal)		
		30	45	60
Thickness	ASTM D1593 Para. 8.1.3	+15% -10%	+15% -10%	+15% -10%
Specific Gravity	ASTM D297	1.20±.05	1.20±.05	1.20±.05
Minimum Tensile Properties (each direction)	ASTM D412 (as modified in Appendix A)			
1. Breaking Factor (pounds/inch width)		36.0	54.0	72.0
2. Elongation at Break (percent)		300	300	300
Tear Resistance (pounds, minimum)	ASTM D624	4	6	8
Low Temperature	ASTM D746 Procedure B	-40°F	-40°F	-40°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	±2	±2	±2
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)			
1. Breaking Factor		±10	±10	±10
2. Elongation at Break		±20	±20	±20
Bonded Seam Strength[2] (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	28.8	43.2	57.6
Water Absorption (percent, maximum)	ASTM D471 158°F, 168 hours	±2	±2	±2
Shore A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 100 hours, 50 pphm 104°F, 20% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days at 240°F			
1. Elongation (percent, minimum)		210	210	210
2. Breaking Factor (pounds/inch width, minimum)		25.2	37.8	50.4

---

[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1D. MATERIAL PROPERTIES

UNSUPPORTED POLYCHLOROPRENE (CR)

Property	Test Method	Gauge (nominal)		
		30	45	60
Thickness	ASTM D1593 Para 8.1.3	+15% -10%	+15% -10%	+15% -10%
Specific Gravity	ASTM D297	1.48±.05	1.48±.05	1.48±.05
Minimum Tensile Properties (each direction)	ASTM D412 (as modified in Appendix A)			
1. Breaking Factor (pounds/inch width)		45.0	67.5	90.0
2. Elongation at Break (percent)		250	250	250
Tear Resistance (pounds, minimum)	ASTM D624	4	6	8
Low Temperature	ASTM D746 Procedure B	-30°F	-30°F	-30°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	±2	±2	±2
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)			
1. Breaking Factor		±10	±10	±10
2. Elongation at Break		±20	±20	±20
Bonded Seam Strength[2] (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	36.0	54.0	72.0
Water Absorption (percent, maximum)	ASTM D471 158°F, 168 hours	±12	±12	±12
Shore A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 100 hours, 50 pphm 104°F, 20% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 70 hours at 212°			
1. Elongation (percent, minimum)		150	150	150
2. Breaking Factor (pounds/inch width, minimum)		38.2	57.4	76.5

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1E. MATERIAL PROPERTIES
UNSUPPORTED HIGH DENSITY POLYETHYLENE (HDPE)

Property	Test Method	Gauge (nominal)	
		80	100
Thickness	ASTM D1593 Para. 8.1.3	±8%	±10%
Specific Gravity (minimum)	ASTM D792 Method A	0.930	0.930
Minimum Tensile Properties (each direction)	ASTM D638		
1. Tensile Strength Yield (pounds/inch width)		120	150
2. Tensile Strength at Break (pounds/inch width)		120	150
3. Elongation at Yield (percent)		10	10
4. Elongation at Break (percent)		500	500
5. Modulus of Elasticity (pounds/sq. in.)		80,000	80,000
Tear Resistance (pounds, minimum)	ASTM D1004	400	500
Low Temperature	ASTM D746 Procedure B	-40° F	-40°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	±3	±3
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)		
1. Tensile Strength Yield		±10	±10
2. Tensile Strength at Break		±10	±10
3. Elongation at Yield		±10	±10
4. Elongation at Break		±10	±10
5. Modulus of Elasticity		±10	±10
Bonded Seam Strength[2] (factory seam, breaking factor ppi width	ASTM D3083 (as modified in Appendix A)	108	135
Environmental Stress Crack (minimum, hours)	ASTM D1693	500	500

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[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1F. MATERIAL PROPERTIES
UNSUPPORTED ETHYLENE-PROPYLENE DIENE MONOMERS (EPDM)

Property	Test Method	Gauge (nominal) 30	45	60
Thickness	ASTM D1593 Para 8.1.3	+15% -10%	+15% -10%	+15% -10%
Specific Gravity	ASTM D297	1.18±.03	1.18±.03	1.18±.03
Minimum Tensile Properties (each direction)	ASTM D412 (as modified in Appendix A)			
1. Breaking Factor (pounds/inch width)		42.0	63.0	84.0
2. Elongation at Break (percent)		300	300	300
Tear Resistance (pounds, minimum)	ASTM D624 Die C	4	6	8
Low Temperature	ASTM D746 Procedure B	-75°F	-75°F	-75°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 240°F, 7 days	±2	±2	±2
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)			
1. Breaking Factor		±10	±10	±10
2. Elongation at Break		±20	±20	±20
Bonded Seam Strength[2] (factory seam, breaking Factor ppi width)	ASTM D3083 (as modified in Appendix A)	33.6	50.4	67.2
Water Absorption (percent, maximum)	ASTM D471 158°F, 168 hours	±2	±2	±2
Shore A Hardness (points)	ASTM D2240 5 second reading	60±10	60±10	60±10
Ozone Resistance	ASTM D1149 7 days, 100 pphm 104°F, 50% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days at 240°			
1. Elongation (percent, minimum)		210	210	210
2. Breaking Factor (pounds/inch width, minimum)		36.0	54.0	72.0

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1G. MATERIAL PROPERTIES

UNSUPPORTED EPICHLOROHYDRIN POLYMERS (CO, ECO)

Property	Test Method	Gauge (nominal)		
		30	45	60
Thickness	ASTM D1593 Para 8.1.3	+15% -10%	+15% -10%	+15% -10%
Specific Gravity	ASTM D297	1.49±.06	1.49±.06	1.49±.06
Minimum Tensile Properties (each direction)	ASTM D412 (as modified in Appendix A)			
1. Breaking Factor (pounds/inch width)		36.0	54.0	72.0
2. Elongation at Break (percent)		200	200	200
Tear Resistance (pounds, minimum)	ASTM D624	4	6	8
Low Temperature	ASTM D746 Procedure B			
1. Homopolymer (CO)		0°F	0°F	0°F
2. Copolymer (ECO)		-20°F	-20°F	-20°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	±2	±2	±2
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)			
1. Breaking Factor		±10	±10	±10
2. Elongation at Break		±25	±25	±25
Bonded Seam Strength[2] (factory seam, breaking Factor ppi width)	ASTM D3083 (as modified in Appendix A)	28.8	43.2	57.6
Water Absorption (percent, maximum)	ASTM D471 158°F, 168 hours	±10	±10	±10
Shore A Hardness (points)	ASTM D2240 5 second reading	70±8	70±8	70±8
Ozone Resistance	ASTM D1149 7 days, 100 pphm 104°F, 20% extension	No Cracks 7X	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days at 240°			
1. Elongation (percent, minimum)		125	125	125
2. Breaking Factor (pounds/inch width, minimum)		30.0	45.0	60.0

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1H. MATERIAL PROPERTIES

UNSUPPORTED CROSSLINKED CHLORINATED POLYETHYLENE (XLCPE)

Property	Test Method	Gauge (nominal)	
		45	60
Thickness	ASTM D1593 Para 8.1.3	±5%	±5%
Specific Gravity	ASTM D297	1.38±.05	1.38±.05
Minimum Tensile Properties (each direction)	ASTM D412 (as modified in Appendix A)		
1. Breaking Factor (pounds/inch width)		54	72
2. Elongation at Break (percent)		300	300
Tear Resistance (pounds, minimum)	ASTM D624 Die C	5	7
Low Temperature	ASTM D746 Procedure B	-40°F	-40°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 7 days	±2	±2
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)		
1. Breaking Factor		±10	±10
2. Elongation at Break		±10	±10
Bonded Seam Strength[2] (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	44	58
Water Absorption (percent, maximum)	ASTM D471 158°F, 168 hours	+10	+10
Shore A Hardness (points)	ASTMD2240 3 second reading	68±8	68±8
Ozone Resistance	ASTM D1149 7 days, 100 pphm, 104°F, 20% extension	No Cracks 7X	No Cracks 7X
Heat Aging	ASTM D573 7 days, 250°F		
1. Breaking Factor (pounds/inch width, minimum)		48	65
2. Elongation (percent, minimum)		200	200
3. Hardness Change (maximum, points)		8	8

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[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1I. MATERIAL PROPERTIES

UNSUPPORTED ELASTICIZED POLYOLEFIN

Property	Test Method	Gauge (nominal)
		20
Thickness	ASTM D1593 Para 8.1.3	+20%, -15%
Specific Gravity	ASTM D297	0.92±.05
Minimum Tensile Properties (each direction)	ASTM D412 Die C (as modified in Appendix A)	
1. Breaking Factor (pounds/inch width)		34
2. Elongation at Break (percent)		500
3. Modulus (force) at 100% elongation (pounds/inch width)		12.6
Tear Resistance (pounds, minimum)	ASTM D1004 Die C	5.1
Low Temperature	ASTM D1790	-76°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	4
Water Extraction	ASTM D1239 (as modified in Appendix A)	-0.35% max.
Volatile Loss	ASTM D1203 Method A	0.5%
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)	
1. Breaking Factor		-10
2. Elongation at Break		-10
3. Modulus at 100% Elongation		+10
Bonded Seam Strength[2] (factory seam, breaking factor ppi width)	ASTM D3083 (as modified in Appendix A)	27.2
Heat Aging	ASTM D573 14 days, 158°F	
1. Breaking Factor (pounds/inch width minimum)		33
2. Elongation at Break (percent)		425
Ozone Resistance	ASTM D1149 100 pphm, 20% strain, 104°F, 7 days	No Cracks 7X

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[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1J. MATERIAL PROPERTIES

UNSUPPORTED CHLOROSULFONATED POLYETHYLENE (CSPE)

	Test	Gauge (nominal)
Property	**Method**	**30**
Thickness	ASTM D1593 Para 8.1.3	+20%, -10%
Specific Gravity	ASTM D297	1.40 ± .10
Minimum Tensile Properties (each direction)	ASTM D882	
1. Breaking Factor (pounds/inch width)		30
2. Elongation at Break (percent)		300
3. Modulus (force) at 100% elongation (pounds/inch width)	ASTM D882	15
Tear Resistance (pounds, minimum)	ASTM D1004 Die C	6
Low Temperature	ASTM D1790 ⅛" mandrel, 4 hours, Pass	-20° F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 211°F, 15 min.	25
Water Extraction	ASTM D1239 (as modified in Appendix A)	-0.35%
Volatile Loss	ASTM D1203 Method A	0.5%
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)	
1. Breaking Factor		-5
2. Elongation at Break		-20
3. Modulus at 100% Elongation		+10
Bonded Seam Strength[2] (factory seam, breaking factor, ppi width)	ASTM D3083 (as modified in Appendix A)	24
Ozone Resistance	ASTM D1149 100 pphm, 20% strain, 104°F, 7 days	No Cracks 7X

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[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 1K. MATERIAL PROPERTIES

UNSUPPORTED OIL RESISTANT POLYVINYL CHLORIDE (PVC-OR)

Property	Test Method	Gauge (nominal) 30
Thickness	ASTM D1593 Para 8.1.3	±5%
Specific Gravity (minimum)	ASTM D792 Method A	1.20
Minimum Tensile Properties (each direction)	ASTM D882	
1. Breaking Factor (pounds/inch width)	Method A or B (1 inch wide)	69
2. Elongation at Break (percent)	Method A or B	300
3. Modulus (force) at 100% elongation (pounds/inch width)	Method A or B	27
Tear Resistance (pounds, minimum)	ASTM D1004	8
Low Temperature	ASTM D1790	0°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 15 min.	5
Water Extraction	ASTM D1239 (as modified in Appendix A)	-0.35% max.
Volatile Loss	ASTM D1203 Method A	0.5%
Resistance to Soil Burial[1] (percent change maximum in original value)	ASTM D3083 120 day soil burial (as modified in Appendix A)	
1. Breaking Factor		- 5
2. Elongation at Break		- 20
3. Modulus at 100% Elongation		+ 10
Bonded Seam Strength[2] (factory seam, breaking factor ppi width)	ASTM D3083 (as modified in Appendix A)	55.2
Hydrostatic Resistance (pounds/square inch minimum)	ASTM D751 Method A	82

See Appendix A, Part 15, Oil Extraction, 7 days, percent maximum change

	Neats Foot	Gulf Harmony #53	Corn (Mazola)	ASTM No. 2
Weight @73.4±3°F	- 5	- 5	- 5	- 5
Weight @158±3°F	- 15	- 15	- 15	- 10
Tensile @73.4±3°F	+5	+10	+10	+10
Tensile @ 158±3°F	+15	+15	+15	+15
Elongation @ 73.4±3°F	- 10	- 10	- 10	- 10
Elongation @ 158±3°F	- 10	- 15	- 10	- 20

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[1] Test value of "after exposure" sample is based on preset sample dimension. 120 day test is required for initial certification.

[2] Factory bonded seam strength is the responsibility of the fabricator.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 2A. MATERIAL PROPERTIES

SUPPORTED CHLORINATED POLYETHYLENE (CPER)

Property	Test Method	Supported Finished Material	
		Type 2	Type 3
Thickness	ASTM D751		
1. Overall (mils, minimum)		27	34
2. Over Scrim (mils, minimum)	Optical Method (Reference Appendix A)	11	11
Minimum Tensile Properties (each direction)			
1. Breaking Strength (pounds, minimum, Fabric)	ASTM D751	120	200
Tear Strength (pounds, minimum)	ASTM D751 Tongue Method 8 x 8 in. sample	25	35
Low Temperature	ASTM D2136 ⅛ in. mandrel 4 hrs., Pass	-40°F	-40°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 1 hr.	2	2
Resistance to Soil Burial[1] (percent change maximum in original values)	ASTM D3083 120 day soil burial, 30 mil sheet (as modified in Appendix A)		
a. Unsupported Sheet			
1. Breaking Factor		- 5	- 5
2. Elongation at Break		- 20	- 20
3. Modulus at 100% Elongation		+10	+10
b. Membrane Fabric Breaking Factor	ASTM D751	- 10	- 10
Bonded Seam Strength (pounds, minimum)	ASTM D751 (as modified in Appendix A)	96	160
Hydrostatic Resistance (pounds/sq. in., minimum)	ASTM D751 Method A, Procedure 1	160	250
Ply Adhesion (each direction pounds/in. width minimum)	ASTM D413 Machine Method Type A	10	8
Percent CPE Resin by Weight of Total Polymer	NSF verification	>50	>50

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[1] Test value of "after exposure" sample is based on precut sample dimension, 120 day test is required for initial certification.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 29. MATERIAL PROPERTIES

SUPPORTED CHLOROSULFONATED POLYETHYLENE (CSPER)

Property	Test Method	Supported Finished Material		
		Type 1	Type 2	Type 3
Thickness	ASTM D751			
1. Overall (mils, minimum)		27	27	34
2. Over Scrim (mils, minimum)	Optical Method (Reference Appendix A)	11	11	11
Minimum Tensile Properties (each direction)	ASTM D751			
1. Breaking Strength - fabric (pounds minimum)		90[2]	120	200
Tear Strength (pounds, minimum)	ASTM D751 Tongue Method 8 x 8 in. sample			
1. Initial		10	25	80
2. After Heat Aging	212°F, 30 days	TBD	TBD	TBD
Low Temperature	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-40°F	-40°F	-40°F
Dimensional Stability (each direction percent change maximum)	ASTM D1204 212°F, 1 hr.	7.5	2	2
Resistance to Soil Burial[1] (percent change maximum in original values)	ASTM D3083 120 day soil burial 30 mil sheet (as modified in Appendix A)			
a. Unsupported sheet				
1. Breaking Factor		- 5	- 5	- 5
2. Elongation at Break		- 20	- 20	- 20
3. Modulus at 100% Elongation		+10	+10	+10
b. Membrane Fabric Breaking Factor	ASTM D751	- 10	- 10	- 10
Bonded Seam Strength (pounds, minimum)	ASTM D751 (As modified in in Appendix A, 12 in./min.)	80	96	180
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Procedure 1	80	160	250
Ozone Resistance	ASTM D1149 (As modified in 7 days, 100 pphm 104°F, ⅛ in. bent loop)	No Cracks 7X	No Cracks 7X	No Cracks 7X
Ply Adhesion (each direction,[3] pounds/in. width minimum)	ASTM D413 Machine Method Type A	10	10	10
Volatile Loss	ASTM D1203 Method A, 30 mil sheet	0.5%	0.5%	0.5%

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Type 1 liner has two values. Coating is stronger than fabric and will withstand 100 pounds.

[3] Film tearing bond is acceptable.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 2C. MATERIAL PROPERTIES

SUPPORTED THERMOPLASTIC NITRILE - PVC

Property	Test Method	Supported Finished Material		
		Type 1	Type 2	Type 3
Thickness	ASTM D751			
1. Overall (mils, minimum)		27	27	33
2. Over Scrim (mils, minimum)	Optical Method (Reference Appendix A)	11	11	11
Minimum Tensile Properties (each direction)	ASTM D751			
1. Breaking Strength - fabric (pounds minimum)		50[2]	100	180
Tear Strength (pounds, minimum)	ASTM D751 Tongue Method 8 x 8 in. sample	8	20	60
Low Temperature	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-20°F	-20°F	-20°F
Dimensional Stability (each direction, percent change maximum)	ASTM D1204 212°F, 1 hr.	7.5	2	2
Resistance to Soil Burial[1] (percent change maximum in original values)	ASTM D3083 120 day soil burial, 30 mil sheet (as modified in Appendix A)			
a. Unsupported Sheet				
1. Breaking Factor		- 20	- 20	- 20
2. Elongation at Break		- 20	- 20	- 20
3. Modulus at 100% Elongation		+30	+30	+30
b. Membrane Fabric Breaking Factor	ASTM D751	- 10	- 10	- 10
Bonded Seam Strength (pounds, minimum)	ASTM D751 (As modified in Appendix A, 12 in./min.)	64	80	144
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Procedure 1	80	160	250
Ozone Resistance	ASTM D1149 (As modified, 7 days, 100 pphm 104°F, ⅛ in. bent loop)	No Cracks 7X	No Cracks 7X	No Cracks 7X
Ply Adhesion (each direction,[3] pounds/in. width minimum)	ASTM D413 Machine Method Type A	8	8	8
Volatile Loss	ASTM D1203 Method A 30 mil sheet	1.0%	1.0%	1.0%

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Type 1 liner has two values. Coating is stronger than fabric and will withstand 80 pounds.

[3] Film tearing bond is acceptable.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 2D. MATERIAL PROPERTIES

SUPPORTED THERMOPLASTIC EPDM

Property	Test Method	Supported Finished Material		
		Type 1	Type 2	Type 3
Thickness	ASTM D751			
1. Overall (mils, minimum)		27	27	33
2. Over Scrim (mils, minimum)	Optical Method (Reference Appendix A)	11	11	11
Minimum Tensile Properties (each direction)	ASTM D751			
1. Breaking Strength - fabric (pounds minimum)		50[2]	100	180
Tear Strength (pounds, minimum)	ASTM D751 Tongue Method 8 x 8 in. sample	10	25	80
Low Temperature	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-20°F	-20°F	-20°F
Dimensional Stability (each direction percent change maximum)	ASTM D1204 212° F, 1 hr.	7.5	2	2
Resistance to Soil Burial[1] (percent change maximum in original values)	ASTM D3083 120 day soil burial, 30 mil sheet (as modified in Appendix A)			
a. Unsupported Sheet				
1. Breaking Factor		- 10	- 10	- 10
2. Elongation at Break		- 20	- 20	- 20
3. Modulus at 100% Elongation		+30	+30	+30
b. Membrane Fabric Breaking Factor	ASTM D751	- 10	- 10	- 10
Bonded Seam Strength (pounds, minimum)	ASTM D751 (As modified in Appendix A, 12 in./min.)	64	80	144
Hydrostatic Resistance (pounds/sq. in. minimum)	ASTM D751 Method A, Procedure 1	80	160	250
Ozone Resistance	ASTM D1149 (As modified, 7 days, 100 pphm 104°F, ⅛ in. bent loop)	No Cracks 7X	No Cracks 7X	No Cracks 7X
Ply Adhesion (each direction,[3] pounds/in. width minimum)	ASTM D413 Machine Method Type A	8	8	8
Volatile Loss	ASTM D1203 Method A 30 mil sheet	0.5%	0.5%	0.5%

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

[2] Type 1 liner has two values. Coating is stronger than fabric and will withstand 80 pounds.

[3] Film tearing bond is acceptable.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

TABLE 2E. MATERIAL PROPERTIES

SUPPORTED ELASTICIZED POLYOLEFIN ALLOY

Property	·Test Method	Supported Finished Material	
		Type A	Type B
Thickness	ASTM D751		
1. Overall (mils, minimum)		30	30
2. Over Scrim (mils, minimum)	Optical Method (Reference Appendix A)	11	9
Minimum Tensile Properties (each direction)	ASTM D751 Grab Method		
1. Breaking Strength - fabric (pounds, minimum)		300	400
Tear Strength (pounds, minimum)	ASTM D751 Tongue Method 8 x 8 in. specimen	60	125
Low Temperature	ASTM D2136 ⅛ in. mandrel, 4 hrs., Pass	-30°F	-30°F
Dimensional Stability (each direction, percent change, maximum)	ASTM D1204 212°F, 1 hr.	2	2
Resistance to Soil Burial[1] (percent change maximum in original values)	ASTM D3083 120 day soil burial, 30 mil sheet (as modified in Appendix A)		
a. Unsupported Sheet			
1. Breaking Factor		- 10	- 10
2. Elongation at Break		- 20	- 20
3. Modulus at 100% Elongation		+15	+15
b. Membrane Fabric Breaking Factor	ASTM D751	- 10	- 10
Bonded Seam Strength (pounds, minimum)	ASTM D751 (As modified in Appendix A)	240	320
Hydrostatic Resistance (pounds/sq. in., minimum)	ASTM D751 Method A, Procedure 1	500	500
Ozone Resistance	ASTM D1149 (As modified, 7 days, 100 pphm 104°F, ⅛ in. bent loop)	No Cracks 7X	No Cracks 7X
Ply Adhesion (each direction pounds/in. width minimum)	ASTM D413 Machine Method Type A	10	10
Volatile Loss	ASTM D1203 Method A 30 mil sheet	-1.0%	-1.0%
Water Extraction	ASTM D1239 (as modified in Appendix A)	-0.35%	-0.35%
Water Absorption (percent gain, maximum)	ASTM D471 14 days @ 158°F 14 days @ 70°F	 2 1	 2 1

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[1] Test value of "after exposure" sample is based on precut sample dimension. 120 day test is required for initial certification.

The physical property values listed are part of a consensus standard being developed by the National Sanitation Foundation. When specifying flexible membrane liners, these tables may provide useful information, but should be used with discretion. These values are preliminary and subject to change.

GLOSSARY OF TERMS RELATING TO LINER TECHNOLOGY

The intent of this glossary is to define the terms used in this Manual. A glossary is considered desirable because of the diverse origins of the liner technology and the broad spectrum of potential users of this Manual. If possible, generally accepted definitions were selected. The sources of each are indicated with the definition. However, if an appropriate definition could not be found, one was prepared. The definitions are presented by area of expertise, thus some definitions may appear more than once. The areas of expertise are:

1. Admix liner materials
2. Asphalt technology
3. Chemistry
4. Hazardous waste management
5. Hydrology
6. Polymeric membrane liners
7. Site construction
8. Soils science and engineering
9. Solid waste management

After the review period, we propose to combine the final revised list of terms into a single list and to eliminate the references to the sources of the definitions which are presented in the attached list.

GLOSSARY

ADMIX LINER MATERIALS

ADMIX - Two or more materials mixed together at or near the waste disposal facility to be lined. These materials include asphalt concrete, portland cement concrete, and mixtures of soil and asphalt or portland cement.

ADMIXTURES - Substances that are added to mortar, stucco, cement plaster and concrete to produce specific results. They may or may not cause a chemical reaction within the above substances, but usually a chemical reaction does occur. Asphalts may be added for waterproofing compounds (Hornbostel, 1978).

COMPACTION - A process of densifying soil cement, soil asphalt, and asphalt concrete by the use of sheepsfoot rollers,rubber-tired rollers,and smooth steel rollers.

HYDRAULIC ASPHALT CONCRETE - See Asphalt Technology Glossary.

SOIL ASPHALT - A compacted mixture of soil and asphalt cement. Cutback or emulsified asphalts are usually avoided.

SOIL CEMENT - A mixture of soil, portland cement and water. As the cement hydrates, the mixture forms a hard, durable, low strength concrete (Day, 1970).

GLOSSARY

ASPHALT TECHNOLOGY

AGGREGATE - A granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or concrete, or alone as in roadway base courses, railroad ballast, etc. (ASTM, D8).

ASPHALT - A dark brown to black semisolid cementitious material consisting principally of bitumens which gradually liquefy when heated and which occur in nature as such or are obtained as residue in the refining or petroleum (Woods, 1960).

ASPHALT CEMENT - A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements and having a penetration at 25°C (77°F) of between 5 and 300, under a load of 100g applied for five seconds (ASTM, D8).

ASPHALT MEMBRANE - A relatively thin layer of asphalt formed by spraying a high viscosity, high softening point asphalt cement in two or more applications over the surface to be covered. It is normally 1/4" thick and buried to protect it from weathering and mechanical damage.

ASPHALT PANEL - A laminate consisting of a core of blended asphalt, mineral fillers, and reinforcing fibers sandwiched between protective sheets and a protective coating of hot-applied asphalt.

BATTEN - In asphalt technology, a strip usually made of asphalt used to seal the joints between asphalt panels.

BITUMEN - A class of black or dark colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed pricipally of relatively high molecular weight hydrocarbons. Asphalts, tars, pitches, and asphaltites are typical examples of bitumen (ASTM, D8).

BLOWN ASPHALT (AIR-BLOWN ASPHALT) - Asphalt produced in part by blowing air through it at a high temperature. If a catalyst, e.g. ferric chloride or phosphorus pentoxide, is used in the air blowing operation, the product is known as catalytically-blown asphalt (Woods, 1960).

COAL TAR - Tar produced by the destructive distillation of bituminous coal (ASTM, D8).

COURSE - See "Lift".

CUTBACK ASPHALT - Asphalt cement that has been liquefied by blending with petroleum solvents which are in this context also called diluents. Upon exposure to atmospheric conditions the diluents evaporate leaving the asphalt cement to perform its function (Asphalt Institute, MS-5).

EMULSIFIED ASPHALT - A mixture of asphalt and water in which the asphalt is held in suspension in the water by an emulsifying agent. Emulsified asphalts may be either cationic or anionic depending on the emulsifying agent used.

HYDRAULIC ASPHALT CONCRETE - Similar to asphalt concrete designed for roadway paving, except that it has a higher mineral filler and asphalt content in order to insure an essentially voidless mix after compaction (Asphalt Institute, MS-12).

LIFT - An applied and/or compacted layer of soil, asphalt, or waste. In a sanitary landfill, a lift is a compacted layer of solid wastes and a top layer of cover material. Also referred to as a course (EPA, 1972).

MASTIC - A mixture of mineral aggregate, mineral filler, and asphalt in such proportions that the mix can be applied hot by pouring or by mechanical manipulation; it forms a voidless mass without being compacted (Asphalt Institute, MS-12).

MINERAL FILLER - A finely divided mineral product of which at least 65% will pass a No. 200 sieve which has a sieve opening of 74 µm. Pulverized limestone is the most common manufactured filler, although other stone dust, silica, hydrated lime, portland cement, and certain natural deposits of finely divided matter are also used (Asphalt Institute, MS-5).

MIX - The amounts of aggregates and asphalt which are combined to give the desired properties in the finished product.

PENETRATION - The consistency of a bituminous material expressed as the distance in tenths of a millimeter (0.1mm) that a standard needle penetrates vertically into a sample of the material under specified conditions of loading, time, and temperature determined by ASTM D5 (ASTM, D8).

PENETRATION GRADE - Classification of asphalt cement into ranges of penetration values specified in ASTM D946.

SOFTENING POINT - Temperature at which a bitumen softens in the ring-and-ball method described in ASTM D2398. Used in the classification of bitumen, parcularly of bitumen intending for roofing, because it is indicative of the tendency of a material to flow at elevated temperatures encountered in service.

VISCOSITY GRADE - Viscosity classification for asphalt cement into ranges specified in ASTM D3381.

GLOSSARY

CHEMISTRY

ABSORPTION - Ability of a porous solid material to hold within its body relatively large quantities of gases or liquids (Bennett, 1947).

ACIDITY - Quantitative capacity of aqueous solutions to react with hydroxyl ions. It is measured by titration with a standard solution of a base to a specified end point. Usually expressed as milligrams of calcium carbonate per litre (EPA, 1977).

ADSORPTION - The adhesion of an extremely thin layer of molecules (of gases, or liquids) to the surface of solids or liquids with which they are in contact (EPA, 1977).

ALKALINITY - The capacity of water to neutralize acids, a property imparted by the water's content of carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates. It is expressed in milligrams of calcium carbonate equivalent per litre (EPA, 1977).

ANALYSIS - The determination of the nature or proportion of one or more constituents of a substance, whether separated out or not (Webster's New World Dictionary).

ASH (FIXED SOLIDS) - The incombustible material that remains after a fuel or solid waste has been burned.

ATTENUATION - Any decrease in the maximum concentration or total quantity of an applied chemical or biological constituent in a fixed time or distance travelled resulting from physical, chemical, and/or biological reaction or transformation (Federal Register, 1978).

BOD_5 (Five Day Biochemical Oxygen Demand) - A measure of the relative oxygen requirements of waste-waters, effluents and polluted waters. BOD values cannot be compared unless the results have been obtained under identical test conditions. The test is of limited value in measuring the actual oxygen demand of surface waters (APHA - AWWA - WPCF, 1975).

COD (Chemical Oxygen Demand) - A measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant (APHA - AWWA - WPCF, 1975).

CONTAMINATION - A substance or substances that renders a body of water, soil, sample, etc. impure, unclean or corrupt by contact (Webster's New World Dictionary).

DIFFUSION - The material permeation of two or more substances due to the kinetic activity of their molecules, so that a uniform mixture or solution results. Diffusion occurs with all forms of matter; it is most rapid for gases, somewhat slower for liquids and for solids in solution.

EXTRACTABLES - Components or substances removable from a solid or liquid mixture by means of an appropriate solvent (Hampel & Hawley, 1976).

HYDROCARBONS - An organic chemical compound containing mainly the elements carbon and hydrogen. Aliphatic hydrocarbons are straight chain compounds of carbon and hydrogen. Aromatic hydrocarbons are carbon-hydrogen compounds based on the cyclic or benzene ring. They may be gaseous (CH_4, ethylene, butadiene), liquid (hexene, benzene), or solid (natural rubber, napthalene, cis-polybutadiene) (Goodrich, 1979).

HYDROGEN SULFIDE (H_2S) - A poisonous gas with the odor of rotten eggs that is produced from the reduction of sulfates and the putrefaction of sulfur containing organic matter (EPA, 1977).

ORGANIC CONTENT - Usually synonymous with volatile solids in an ashing test; e.g. a discrepancy between volatile solids and organic content can be caused by small traces of some inorganic materials such as calcium carbonate that lose weight at temperatures used in determining volatile solids (EPA, 1972).

OSMOSIS - The diffusion of fluids through a semi-permeable membrane or porous partition (Webster's New World Dictionary).

pH - (1) The negative log of the hydrogen ion concentration, a measure of acidity and alkalinity (EPA, 1972). (2) A measure of the relative acidity or alkalinity of water. A pH of 7.0 indicates a neutral condition. A greater pH indicates alkalinity and a lower pH, acidity. A one unit change in pH indicates a tenfold change in acidity and alkalinity (Houston, 1974).

SOLUBILITY - The amount of a substance that can be dissolved in a given solvent under specified conditions (Webster's New World Dictionary).

SUSPENDED SOLIDS - Solids that either float on the surface of or are in suspension in water, wastewater, or other liquids, and which are largely removable by laboratory filtering as described in "Standard Methods of the Examination of Water and Wastewater", and referred to as nonfilterable residue (EPA, 1977).

VOLATILE ACIDS - Lower acids up to and including capric acid, which are volatile, will vaporize, evaporate, or distill off, with steam (Bennett, 1947).

VOLATILE SOLIDS - The material lost from a dried solid waste sample that is heated until it is red in an open crucible in a ventilated furnace. The weight of volatile solids is equal to that of the volatile matter plus that of the fixed carbon (EPA, 1972).

GLOSSARY

HAZARDOUS WASTE MANAGEMENT

ACIDIC WASTE - A waste that has a low pH.

AERATION SYSTEM - A system which exposes a bulk material, such as a compost, to air or which charges a liquid with a gas or a mixture of gases (EPA, 1972).

BIODEGRADABLE - Susceptible to decomposition as a result of attack by microorganisms - said of organic materials (Hempel and Hawley, 1976).

CHEMICAL FIXATION - Treatment process which involves reactions between the waste and certain chemicals, and which results in solids which encapsulate, immobilize or otherwise tie up hazardous components in the waste so as to minimize the leaching of hazardous components and render the waste nonhazardous or more suitable for disposal.

COLLECTION (DRAINAGE) SYSTEM - Structures and facilities for collecting and carrying away water or other liquid (Asphalt Institute, MS-15).

COMPATIBILITY - Capability of existing together without adverse effects. Applied primarily to combinations of waste fluids and liner materials.

FACILITY - Any land and appurtenances thereon and thereto, used for treatment, storage and/or disposal of hazardous waste (Fed. Reg., 1978).

FLY ASH - All solids, including ash, charred paper, cinders, dust, soot, or other partially incinerated matter that are carried in a gas stream (EPA, 1972).

HAZARDOUS WASTE - A solid waste or combination of solid wastes, which because of its quantity, concentration or physical, chemical, or infectious characteristics may:

A. cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or

B. pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed (Public Law 94-580, 1976).

HEAVY METALS - A general name given to the ions of metallic elements such as copper, zinc, chromium, or aluminum. They are normally removed from a wastewater by forming an insoluble precipitate, usually a metallic hydroxide (EPA, 1977).

HERBICIDE - A type of pesticide, including so called weed-killers,silvicides and defoliants, which kills or otherwise eliminates shrubs, small trees, grasses, etc. There are both organic and inorganic herbicides: the latter is typified by common salt, sodium borate, and various arsenical compounds; the formed by 2,4-D and similar chlorinated compounds and by the defoliant picloram (EPA, 1977).

IMPOUNDMENT - See "Surface Impoundment" in Site Construction Glossary.

INDUSTRIAL WASTE - The liquid wastes from industrial processes as distinct from domesticor sanitary waste (EPA, 1977).

LEACHATE - See Solid Waste Management Glossary.

LINER - See Solid Waste Management Glossary.

MONITORING - All procedures used to systematically inspect and collect data on operational parameters of a facility or on the quality of the air, groundwater, surface water or soil.

MONITORING WELL - A well used to obtain water samples for water quality analysis or to measure groundwater levels.

PESTICIDE - See Solid Waste Management Glossary.

SOLID WASTE - See Solid Waste Management Glossary.

SUMP - A pit or well in which liquids collect (Webster's New World Dictionary).

TOXICANT - A toxic agent, especially one for insect control, that kills rather than repels (Webster's Collegiate Dictionary).

TOXIN - (1) Any of various unstable poisonous compounds produced by some microorganisms and causing certain diseases. (2) Any of various similar poisons, related to proteins, secreted by plants and animals (Webster's New World Dictionary).

GLOSSARY

HYDROLOGY

AQUIFER - A geologic formation, group of formations or part of a formation that is capable of yeilding usable quantities of groundwater to wells or springs (Fed. Reg., 1978).

CAPILLARY WATER - Underground water that is held above the water table by capillary action (EPA, 1972).

DISSOLVED SOLIDS - Solids or particles small enough to be part of a solution. Dissolved solids will pass through a glass fiber filter (APHA - AWWA - WPCF).

FLUX - (1) A bituminous material (generally liquid) used for softening other bituminous materials. (2) The rate of flow of a solute through a porous medium; or more technically, the volume of flow per unit time per unit area perpendicular to the direction of flow referred to as the Darcian velocity of flux density (Fuller, 1978).

GROUNDWATER, FREE - (1) Groundwater in aquifer (2) Water in the saturated zone beneath the land surface (Fed. Reg. 12/18/78).

GROUNDWATER TABLE - See "Water Table".

HEAD, (PRESSURE) - Pressure measured as an equivalent height of water.

HYDRAULIC GRADIENT - The change in hydraulic pressure per unit of distance in a given direction.

HYDROLOGY - Science dealing with the properties, distribution and flow of water on or in the earth (EPA, 1972).

RUN OFF - That portion of precipitation or irrigation water that drains from an area as surface flow (EPA, 1972).

SLOPE - Deviation of a surface from the horizontal expressed as a percentage, by ratio, or in degrees (EPA, 1972).

WATER TABLE, PERCHED - A water table, usually of limited area, maintained above the normal free-water elevation by the presence of an intervening; relatively impervious stratum (EPA, 1972).

WATER TABLE - (1) The upper limit of the part of the soil or underlying rock material that is wholly saturated with water (EPA, 1972). (2) The upper surface of the zone of saturation in groundwaters in which the hydrostatic pressure of equal to atmospheric pressure (Fed. Reg., 1978).

ZONE OF AERATION - Area above a water table where the interstices (pores) are not completely filled with water (EPA, 1972).

ZONE OF CAPILLARITY - The area above a water table where some or all of the interstices (pores) are filled with water that is held by capillary action (EPA, 1972).

GLOSSARY

POLYMERIC MEMBRANE LINER TECHNOLOGY

ADHESION - The state in which two surfaces are held together by interfacial forces which may consist of molecular forces or interlocking action or both. Measured in shear and peel modes. (B.F. Goodrich, 1979).

AIR LANCE - A device used to test, in the field, the integrity of field seams in plastic sheeting. It consists of a wand or tube through which compressed air is blown.

ALLOYS, POLYMERIC - A blend of two or more polymers, e.g. a rubber and a plastic to improve a given property, e.g. impact strength.

ANCHOR TRENCH - A long narrow ditch on which the edges of a plastic sheet are buried to hold it in place or to anchor the sheet.

BERM - The upper edge of a pit or pond where a membrane liner is anchored. The berm may be wide and solid enough for vehicular traffic.

BLOCKING - Unintentional adhesion usually occurring during storage or shipping between plastic films or between a film and another surface (ASTM D883).

BODIED SOLVENT ADHESIVE - An adhesive consisting of a solution of the liner compound used in the seaming of liner membranes.

BOOT - A bellows type covering to exclude dust, dirt, moisture, etc., from a flexible joint (B.F. Goodrich, 1979).

BREAKING FACTOR - Tensile at break in force per unit of width; units, SI: Newton per meter, customary: pound per inch.

BUTYL RUBBER - A synthetic rubber based on isobutylene and a minor amount of isoprene. It is vulcanizable and features low permeability to gases and water vapor and good resistance to aging, chemicals, and weathering.

CALENDER - A precision machine equipped with three or more heavy internally heated or cooled rolls, revolving in opposite directions. Used for preparation of highly accurate continuous sheeting or plying up of rubber compounds and frictioning or coating of fabric with rubber or plastic compounds (B.F. Goodrich, 1979).

CHLORINATED POLYETHYLENE (CPE) - Family of polymers produced by chemical reaction of chlorine on the linear backbone chain of polyethylene. The resultant rubbery thermoplastic elastomers presently contain 25-45% chlorine by weight and 0-25% crystallinity. CPE can be vulcanized but is usually used in a nonvulcanized form.

CHLOROSULFONATED POLYETHYLENE (CSPE) - Family of polymers that are produced by polyethylene reacting with chlorine and sulfur dioxide. Present polymers contain 25-43% chlorine and 1.0-1.4% sulfur. They are used in both vulcanized and nonvulcanized forms. Most membranes based on CSPE are nonvulcanized. ASTM designation for this polymer is CSM.

COATED FABRIC - Fabrics which have been impregnated and/or coated with a plastic material in the form of a solution, dispersion, hotmelt, or powder. The term also applies to materials resulting from the application of a preformed film to a fabric by means of calendering.

CROSSLINKING - A general term referring to the formation of chemical bonds between polymeric chains to yield an insoluble, three dimensional polymeric structure. Crosslinking of rubbers is vulcanization, qv.

CURING - See "Vulcanization".

DENIER - A unit used in the textile industry to indicate the fineness of continuous filaments. Fineness in deniers equals the mass in grams of 9000 meter length of the filament.

DIELECTRIC SEAMING - See "Heat Seaming".

ELASTICITY - The property of matter by virtue of which it tends to return to its original size and shape after removal of the stress which caused the deformation (B.F.Goodrich, 1979).

ELASTOMER - See "Rubber".

EPDM - A synthetic elastomer based on ethylene, propylene, and a small amount of a nonconjugated diene to provide sites for vulcanization. EPDM features excellent heat, ozone and weathering resistance, and low temperature flexibility.

EPICHLOROHYDRIN RUBBER - This synthetic rubber includes two epichlorohydrin-based elastomers which are saturated, high molecular weight, aliphatic polyethers with chloro-methyl side chains. The two types include a homopolymer (CO) and a copolymer of epichlorohydrin and ethylene oxide (ECO). These rubbers are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group; including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium sualts.

EVA - Family of copolymers of ethylene and Vinyl Acetate used for adhesives and thermoplastic modifiers. They possess a wide range of melt indexes.

EXTRUDER - A machine with a driven screw for continuous forming of rubber by forcing through a die; can be used to manufacture films and sheeting.

FABRIC-REINFORCEMENT - A fabric, scrim, etc., used to add structural strength to a 2 or more ply polymeric sheet. Such sheeting is referred to as "supported".

FILL - As used in textile technology refers to the threads or yarns in a fabric running at right angles to the warp. Also called filler threads. (Rubber Manufacturers Assn., 1969).

FILM - Sheeting having nominal thickness not greater than 10 mils (ASTM, D883).

HEAT SEAMING - The process of joining two or more thermoplastic films or sheets by heating areas in contact with each other to the temperature at which fusion occurs. The process is usually aided by a controlled pressure. In dielectric seaming the heat is induced within films by means of radio frequency waves.

LAPPED JOINT - A joint made by placing one surface to be joined partly over another surface and bonding the overlapping portions (Whittington, 1968).

LENO FABRIC - An open fabric in which two warp yarns wrap around each fill yarn in order to prevent the warp or fill yarns from sliding over each other.

MEMBRANE - In this Manual the term membrane applies to a continuous sheet of material whether it is prefabricated as a flexible polymeric sheeting or is sprayed or coated in the field, such as a sprayed-on asphalt.

NEOPRENE (POLYCHLOROPRENE) - Generic name for a synthetic rubber based primarily on chloroprene, i.e. chlorobutadiene. Vulcanized generally with metal oxide. Resistant to ozone and aging and to some oils.

NITRILE RUBBER - A family of copolymers of butadiene and acrylonitrile that can be vulcanized into tough oil resistant compounds. Blends with PVC are used where ozone and weathering are important requirements in addition to its inherent oil and fuel resistance.

NYLON - Generic name for a family of polyamide polymers characterized by the presence of the amide group -CONH. Used as a scrim in fabric reinforced sheeting (Cond. Chem. Dict., 1977).

PERMEABILITY - (1) The capacity of a porous medium to conduct or transmit fluids (ASCE,1976). (2) The amount of liquid moving through a barrier in a unit time, unit area, and unit pressure gradient not normalized for but directly related to thickness (Wren, 1972).

PLASTIC - A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state and at some stage in its manufacture or processing into finished articles, can be shaped by flow (ASTM D883).

PLASTICIZER - A plasticizer is a material, frequently "solvent-like", incorporated in a plastic or a rubber to increase its ease of workability, its flexibility, or extensiblity. Adding the plasticizer may lower the melt viscosity, the temperature of the second order transition, or the elastic modulus of the polymer.

Plasticizers may be monomeric liquids (phthalate esters), low molecular weight liquid polymers (polyesters) or rubbery high polymers (E/VA).

The most important use of plasticizers is with PVC where the choice of plasticizer will dictate under what conditions the liner may be used.

POLYESTER FIBER - Generic name for a manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of an ester of a dihydric alcohol and terephthalic acid. Scrims made of polyester fiber are used for fabric reinforcement.

POLYMER - A macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high molecular weight polymers.

POLYMERIC LINER - Plastic or rubber sheeting used to line disposal sites, pits, ponds, lagoons, canals, etc.

POLYVINYL CHLORIDE (PVC) - A synthetic thermoplastic polymer prepared from vinylchloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of sheeting.

PUNCTURE RESISTANCE - Extent to which a material is able to withstand the action of a sharp object without perforation. Examples of test of this property are Federal Test Method Standard No. 101B, Methods 2031 or 2065.

ROLL GOODS - A general term applied to rubber and plastic sheeting whether fabric reinforced or not. It is usually furnished in rolls.

RUBBER - A polymeric material which, at room temperature, is capable of recovering substantially in shape and size after removal of a deforming force. Refers to both synthetic and natural rubber. Also called an elastomer.

SCRIM - A woven, open mesh reinforcing fabric made from continuous filament yarn. Used in the reinforcement of polymeric sheeting (Whittington, 1968).

SEAM STRENGTH - Strength of a seam of liner material measured either in shear or peel modes. Strength of the seams is reported either in absolute units, e.g. pounds per inch of width, or as a percent of the strength of the sheeting.

SHEETING - A form of plastic or rubber in which the thickness is very small in proportion to length and width and in which the polymer compound is present as a continuous phase throughout, with or without fabric.

STRIKETHROUGH - A term used in the manufacture of fabric-reinforced polymeric sheeting to indicate that two layers of polymer have made bonding contact through the scrim.

SUPPORTED SHEETING - See "Fabric-Reinforcement".

SURFACE CURE - Curing or vulcanization which occurs in a thin layer on the surface of a manufactured polymeric sheet or other items.

TEAR STRENGTH - The maximum force required to tear a specified specimen, the force acting substantially parallel to the major axis of the test specimen. Measured in both initiated and uninitiated modes. Obtained value is dependent on specimen geometry, rate of extension, and type of fabric reinforcment. Values are reported in stress, e.g. pounds, or stress per unit of thickness, e.g. pounds per inch.

TENSILE STRENGTH - The maximum tensile stress per unit of original cross-sectional area applied during stretching of a specimen to break; units: SI-metric-Megapascal on kilopascal, customary - pound per square inch.

THERMOPLASTIC - Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature. Most polymeric liners are supplied in thermoplastic form because the thermoplastic form allows for easier seaming both in the factory and on the field.

THERMOPLASTIC ELASTOMERS - New materials which are being developed, and which are probably related to elasticized polyolefins. Polymers of this type behave similarly to crosslinked rubber. They have a limited upper temperature service range which, however, is substantially above the temperature encountered in waste disposal sites (200°F may be too high for some TPE's).

THREAD COUNT - The number of threads per inch in each direction with the warp mentioned first and the fill second, e.g. a thread count of 20 x 10 means 20 threads per inch in the warp and 10 threads per inch in the fill direction.

ULTIMATE ELONGATION - The elongation of a stretched specimen at the time of break. Usually reported as percent of the original length. Also called elongation at break.

UNSUPPORTED SHEETING - A polymer sheeting one or more plies thick without a reinforcing fabric layer or scrim.

VULCANIZATE - A term used to denote the product of the vulcanization of a rubber compound without reference to shape or form.

VULCANIZATION - An irreversible process during which a rubber compound, through a change in its chemical structure, e.g. crosslinking, becomes less plastic and more resistant to swelling by organic liquids, and elastic properties are conferred, improved, or extended over a greater range of temperature (ASTM, STP 184A-1972).

WARP - In textiles, the lengthwise yarns in a woven fabric (Rubber Manufacturers Assn., 1969).

WATER VAPOR TRANSMISSION (WVT) - Water vapor flow normal to two parallel surfaces of a material, through a unit area, under the conditions of a specified test such as ASTM E96.

GLOSSARY

SITE CONSTRUCTION

ANCHOR TRENCH - See "Polymeric Membrane Liner Technology Glossary".

BLADE - A heavy broad metal plate attached to the front of a tractor.

U-"Universal" - A blade with extensions on each side that protrude forward at an obtuse angle to the blade and enable it to handle a larger volume than a regular blade.

Landfill: A U-blade with an extension on top that increases the volume of solid wastes that can be pushed and spread, and protects the operator from debris thrown out of the solid waste.

COURSE - See "Lift".

COVER, FINAL - The cover material that is applied at the end of the useful life of a disposal site and represents the permanently exposed final surface of the fill.

COVER MATERIAL - A soil or other suitable material that is used to cover the liner or wastes in a disposal site.

CUT AND COVER (CUT AND FILL) - An infrequently and incorrectly used term referring to the trench method of sanitary landfilling (EPA, 1972).

CUT-OFF TRENCH - A trench that is filled with material that may be impermeable or very permeable to the flow of a gas or water. The barrier is used to prevent the movement of gas or water or to intercept them and to direct them to another location (EPA, 1972).

DRAINAGE - Provision for directing the runoff that occurs from precipitation or overland flow in such a way as to prevent contact with refuse or interference with landfill operations (ASCE, 1976).

EARTHEN DIKE - A dam constructed of soil and earth.

GEOTEXTILE - A textile fabric, such as a filter fabric used in civil engineering applications.

GRADE - (1) See "Gradient". (2) To level off to a smooth horizontal or sloping surface. (3) A datum or reference level. (4) Particle sized distribution of an aggregate.

GRADIENT - The degree of slope or a rate of change of a parameter measured over distance (EPA, 1972).

GROUT - A cementing or sealing mixture of cement and water to which sand, sawdust or other fillers may be added (EPA, 1972).

IMPOUNDMENT - See "Surface Impoundment".

LIFT - A single layer of compacted soil. Lift thickness depends on soil and degree of compaction needed (also termed "course").

ROLLER - A heavy cylinder of metal, stone, etc., used to crush, compact, or smooth a surface (Webster's New World Dict.).

SEEPAGE - Movement of water or gas through soil without forming definite channels (EPA, 1972).

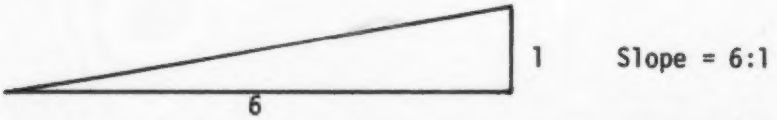
SETTLEMENT - A gradual subsidence of material (EPA, 1972).

SETTLEMENT DIFFERENTIAL - Nonuniform subsidence of material from a fixed horizontal reference plane (ASCE, 1976). More commonly known as "Differential Settlement".

SHEEPSFOOT ROLLER - A tamping roller with numerous closely spaced "feet", or solid cylinders, approximately 6 inches long with a tamping area of about 2 inches. It is often used in the compacting of soils.

SITE - Jobsite.

SLOPE - Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees. In engineering, usually expressed as a ratio of horizontal:vertical change (EPA, 1972).



SPRAY BAR - A long hollow tube with nozzles of any of a number of forms, used to apply a thin layer or coat of a substance in liquid form. Spray bars are attached by hoses and pneumatic lines to pumps to convey the liquid from the storage truck or tank to the nozzles.

STABILIZATION - A stabilizing procedure or to make stable, to firm, as applied to a soil.

SUBGRADE - The foundation or supporting soil layer for a liner. Subgrades can be the surface of the ungraded native soil, but are more commonly specially prepared, artifically compacted layers of soil.

SUBSIDENCE - Settling or sinking of the land surface due to many factors such as the decomposition of organic material, consolidation, drainage, and underground failure (EPA, 1972).

SUBSOIL - That part of the soil beneath the topsoil, usually not having an appreciable organic matter content (EPA, 1972).

SURFACE COMPACTION - Increasing the dry density of surface soil by applying a dynamic load (EPA, 1972).

SURFACE CRACKING - Discontinuities that develop in the cover material at a sanitary landfill due to the surface drying of the cover or settlement of the solid waste. Such discontinuities can permit entrance or egress of vectors, intrusion of water, and venting of decomposition gases (EPA, 1972).

SURFACE IMPOUNDMENT - A natural topographic depression, artificial excavation, or dike arrangement with the following characteristics: (1) it is used primarily for holding, treatment, or disposal of waste; (2) it may be constructed above, below, or partially in the ground or in navigable waters (e.g., wetlands); and (3) it may or may not have a permeable bottom and/or sides. Examples include holding ponds and aeration ponds (Fed. Reg., 1978).

VENT - A small hole or opening to permit passage or escape, as of a gas (Webster's New World Dictionary).

GLOSSARY

SOILS SCIENCE AND ENGINEERING

AIR DRY - (1) The state of dryness (of a soil) at equilibrium with the moisture content in the surrounding atmosphere. The actual moisture content will depend on the relative humidity and the temperature of the surrounding atmosphere. (2) To allow to reach equilibrium in moisture content with the surrounding atmosphere (SSSA, 1970).

AIR POROSITY - The proportion of the bulk volume of soil that is filled with air at any given time or under a given condition such as a specified moisture tension (SSSA, 1970).

ALLUVIUM - A general term for all detrital material deposited or in transit by streams, including gravel, sand, silt, clay and all variations and mixtures of these. Unless otherwise noted, alluvium is unconsolidated (Brady, 1974).

AMPHOTERIC - Having the property of reacting with either an acid or a base. Many oxides and salts have this ability (aluminum hydroxide, for example) (Hampel and Hawley, 1976).

ANION EXCHANGE CAPACITY - The sum total of exchangeable anions that a soil can absorb. Expressed as milliequivalents per 100 gram of soil (or other absorbing materials such as clay) (SSSA, 1970).

ATTERBERG LIMITS - Moisture content values which are measured for soil materials passing a no. 40 sieve and which define soil plasticity properties. Also referred to as plasticity limits. The Atterberg limits are as follows:

Shrinkage Limit (SL): The maximum water content at which a reduction in water content will not cause a decrease in the volume of the soil mass. This defines the arbitrary limit between the solid and semi-solid states.

Plastic Limit (PL): The water content corresponding to an arbitrary limit between the plastic and semi-solid states of consistency of a soil.

Liquid Limit (LL): The water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil (Brady, 1974).

BEDROCK - The solid rock underlying soils and the regolith at depths from zero (where exposed by erosion) to several hundred feet (Brady, 1974).

BENTONITE - A soft clay formed as a weathering product from volcanic ash and composed chiefly of the mineral montmorillonite. Sodium bentonite is notable for its ability to swell in water.

CATION EXCHANGE CAPACITY - The sum total of exchangeable cations that a soil can absorb; sometimes called "total exchange capacity", "base-exchange capacity" or "cation absorption capacity". Expressed in milliequivalents per 100 grams of soil (or of other absorbing material such as clay).

CALIFORNIA BEARING RATIO (CBR) - The ratio of (1) the force per unit area required to penetrate a soil mass with a 3 in.^{2} circular piston (approximately 2 in. diameter) at the rate of 0.05 in./min. to (2) the force per unit area required for corresponding penetration of a standard material. Also known as the bearing ratio of laboratory compacted soils (ASTM D653, D1883).

CLAY - Term is used in three ways: (1) Soil particles less than two micrometers in equivalent diameter. Cf. sand, silt. (2) A secondary soil mineral formed through weathering of primary minerals or transported. Mainly aluminosilicates, some relevant characteristics are:

1. Large surface area.
2. Hydration/dehydration.
3. Cation exchange capacity.
4. Particles less than two micrometers.
5. Flocculation/dispersion.

(3) Soil material containing more than 40% clay, less than 45% sand and less than 40% silt.

CLAY MINERAL - (1) Naturally occurring inorganic crystalline material found in soils and other earthy deposits, the particles being of clay size, i.e., <2 mm in diameter. (2) Material as described under (3) but not limited by particle size (SSSA, 1970).

COEFFICIENT OF PERMEABILITY - See PERMEABILITY.

COHESION - That part of soil strength that is present independently of any applied pressures, either mechanical or capillary, and would remain, though not necessarily permanently, if all applied pressures were removed.

COMPACTION - Compression of a mass to decrease its volume or the thickness of a layer by reduction of voids.

DARCY'S LAW - A law describing the rate of flow of water through porous media.

DISPERSED STRUCTURE - A soil structure wherein the clay particles are associated primarily in a random, parallel array.

DOUBLE LAYER - In colloid chemistry, the electric charges on the surface of the disperse phase (usually negative), and the adjacent diffuse layer (usually positive) of ions in solution (SSSA, 1970).

EXCHANGEABLE SODIUM PERCENTAGE - The extent to which the absorption complex of a soil is occupied by sodium. It is expressed as follows:

$$\mathrm{ESP} = \frac{\text{Exchangeable sodium (meq/100g soil)}}{\text{Cation-exchange capacity (meq/100g soil)}}$$

FLOCCULATED STRUCTURE - A soil structure wherein the clay particles are associated primarily in a random, predominantly edge-to-face arrangement with essentially solid contact in the areas of closest approach (Mitchell and Chan, 1960).

GRAVITATIONAL WATER - Water which moves into, through, or out of the soil under the influence of gravity.

HYDRAULIC CONDUCTIVITY - See "Permeability".

INFILTRATION RATE (INFILTRATION CAPACITY) - A soil characteristic determining the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. It has the dimensions of velocity (SSSA, 1970).

INFILTRATION VELOCITY - the actual rate at which water is entering the soil at any given time. It may be less than the maximum (the infiltration rate) because of a limited supply of water (rainfall or irrigation). It has the same units as infiltration rate (SSSA, 1979).

INTRINSIC PERMEABILITY - The property of a porous material that relates to the ease with which gases or liquids can pass through it. The Darcy "k" is multiplied by n'/g to obtain K', the intrinsic permeability, where:

n' is the kinematic viscosity of the fluid in $\mathrm{cm}^2\ \mathrm{sec}^{-1}$

g is the acceleration of gravity in $\mathrm{cm/sec}^2$

$n' = n/p$

where, n is viscosity in poises, g cm^{-1} sec^{-1}

p is density of the fluid in g cm^{-3}

For water at 23°C and $q = 981$ an SEC^{-1}, the relationship between permeability, K, and intrinsic permeability K' is expressed by the equation

$$K' = (0.91 \times 10^{-5} \text{ cm sec})(K)$$

INTERLAYER - Materials between layers, including cations, hydrated cations, organic molecules and hydroxide groups or sheets. Refers to clay mineralogy microstructure (SSSA, 1970).

INTERLAYER (OR BASAL) SPACING - The space between layers in clay microstructure.

ISOMORPHOUS SUBSTITUTION - The replacement of one atom by another of similar size and lower charge (valence) in a crystal lattice without significantly disrupting or changing the crystal structure of the mineral (SSA, 1970).

ISOTROPIC SOIL - A soil in which a certain property at a point is the same in all directions through that point.

KAOLIN - (1) An alumino-silicate mineral of the 1:1 crystal lattice group; that is, consisting of one silicon tetrahedral layer and one aluminum oxide-hydroxide octahedral layer. (2) The 1:1 group or family of alumino-silicates (SSSA, 1979).

LOAM - A textural class name for soil having a moderate amount of sand, silt, and clay. Loam soils contain 7-28% clay, 28-50% silt, and less than 52% sand (Brady, 1974).

MOISTURE CONTENT - The weight loss (expressed in %) when a sample of soil or waste is dried to a constant weight at 100-105 C (EPA, 1972).

MOISTURE CONTENT, OPTIMUM - The water content at which a soil-like mass can be compacted to a maximum dry unit weight by a given compactive effort.

MOISTURE RETENTION CURVE - A graph showing the soil moisture percentage (by weight or by volume) versus applied tension. Points on the graph are obtained by increasing or decreasing the applied tension over a specified range (SSSA, 1970).

MOISTURE TENSION (OR PRESSURE) - The equivalent negative pressure in the soil water. It is the equivalent pressure that must be applied to the soil water to bring it to hydraulic equilibrium, through a porous permeable wall or membrane, with a pool of water of the same composition (SSSA, 1979).

MOISTURE-WEIGHT PERCENTAGE - The moisture content expressed as a percentage of the oven-dry weight of soil (SSSA, 1970).

MONTMORILLONITE - An alumino-silicate clay mineral with a 2:1 expanding crystal structure; that is, with two silicon tetrahedral layers enclosing an aluminum octahedral layer. Considerable expansion may be caused along the axis by water moving between silica tetrahedra of neighboring layers.

OVENDRY SOIL - Soil which has been dried at 105°C until it reaches a constant weight (SSA, 1979).

PARTICLE DENSITY - The mass per unit volume of the soil particles. In technical work, usually expressed as g/cm^3 (SSSA, 1970).

PARTICLE SIZE - The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods (SSSA, 1970).

PARTICLE SIZE DISTRIBUTION - The amounts of the different soil particles in a soil sample, usually expressed in weight percentages (SSSA, 1970).

PERCOLATION, SOIL WATER - Downward movement of water through soil. Especially, the downward flow of water in saturated or near saturated soil at hydraulic gradients of the order of 1.0 or less (SSSA, 1979) (ASTM, D653, 1979).

PERMEABILITY - A numerical measure of the ability of a soil to transmit a fluid (typically water). Permeability, K, is a constant of proportionality under conditions of laminar flow, such that the Darcy relationship is valid. Permeability has dimensions of velocity, i.e., cm sec^{-1}.

PLASTICITY INDEX (PLASTICITY NUMBER) (PLASTICITY RANGE) - The numerical difference between the liquid limit and the plastic limit.

PLASTIC LIMIT - See Atterberg limits.

PLATY - Consisting of soil aggregates that are developed predominantly along horizontal axes; laminated, flaky (SSSA, 1970).

PORE-SIZE DISTRIBUTION - The volume of various sizes of pores in a soil. Expressed as a percentage of bulk volume, i.e., total volume of solids and pores (SSSA, 1970).

POROSITY - The volume percentage of the total bulk not occupied by solid particles (SSSA, 1970).

POTASSIUM FIXATION - The process of converting exchangeable to nonexchangeable potassium (adapted from SSSA, 1970).

PROCTOR (COMPACTION TEST) - Standard proctor or standard AASHTO test used to determine the proper amount of mixing water to use when compacting a soil test in the field and the resulting degree of density which can be expected from compaction at this optimum water content (Lambe, 1951).

SAND - Soil particles between 0.05 and 2 mm in diameter (Brady, 1974).

SANDY LOAM - A soft easily worked soil containing 0-20% clay, 0-5% silt and 43-85% sand according to the US Department of Agriculture (EPA, 1972).

SHRINK/SWELL - Volume change due to build-up and release of capillary tensile stress within the soil's pore water (Asphalt Institute, MS-10).

SILT - (1) Soil particles which pass thorugh a No. 200 sieve and are larger than 0.002 mm in equivalent diameter. (2) Soil textural class (Brady, 1974).

SOIL - The unconsolidated natural surface material present above bedrock; either residual in origin (formed by the in-place weathering of bedrock) or placed by the wind, water, or gravity (EPA, 1972).

SOIL PIPING OR TUNNELING - Accelerated erosion which results in subterranean voids and tunnels (SSSA, 1970).

SOIL SOLUTION - The aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials (Brady, 1974).

SOIL STERILANT - Biocide applied to soils to prevent plant growth and insect infestation.

SOIL STRUCTURE - The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively (SSSA, 1970).

SURFACE SEALING - The orientation and packing of dispersed soil particles in the immediate surface layer of the soil, rendering it relatively impermeable to water (SSSA, 1970).

TACTOID - An agglomeration of clay particles.

TEXTURE - The relative proportions of various particle size classes (clay, silt, sand) in a soil (Brady, 1974).

THIXOTROPY - An isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby a material stiffens while at rest and softens or liquifies upon remolding (Mitchell, 1960).

UNSATURATED FLOW - The movement of water in a soil which is not filled to capacity with water (SSSA, 1970).

VOID RATIO - Volumetric proportion in a bulk volume of soil between voids and solid soil.

WATER STABLE AGGREGATE - A soil aggregate which is stable to the action of water such as falling drops or agitation as in wet sieve analysis (SSSA, 1970).

GLOSSARY
SOLID WASTE MANAGEMENT

AQUIFER - See Hydrology Glossary.

BIODEGRADABLE - See Hazardous Waste Glossary.

BOD_5 - See Chemistry Glossary.

CARCINOGEN - See Chemistry Glossary.

CELL - Portion of waste in a landfill which is isolated horizontally and vertically from other portions of waste in the landfill by means of soil barrier (Federal Reg.,1978).

COD - See Chemical Glossary.

COLLECTION SYSTEM - See Hazardous Waste Glossary.

COMPATIBILITY - See Hazardous Waste Glossary.

COVER, DAILY - The cover material that is applied over compacted wastes in a working landfill at the end of each operating day.

DENSITY -

Sanitary Landfill: Ratio of the combined weight of solid waste and the soil cover to the combined volume of the solid waste and the soil cover:

$$\frac{W_{SW} \;\&\; W_{soil}}{V_{SW} \;\&\; V_{soil}}$$

Solid Waste: The number obtained by dividing the weight of solid waste by its volume (EPA, 1972).

DISSOLVED SOLIDS - See Chemistry Glossary.

EFFLUENT (1) A liquid which flows out of a containing space; (2) Sewage water or other liquids partially or wholly flowing out of a reservoir basin or treatment plant or part thereof (EPA, 1977).

FACILITY - Any land and appurtenances thereon and thereto, used for treatment, storage and/or disposal of hazardous waste (Federal Reg., 1978).

FIELD CAPACITY - the maximum amount of moisture a soil or solid waste can retain in a gravitional field without a continuous downward percolation (Fenn, 1975).

IMPERMEABLE - Not permitting passage of a fluid or a gas through its substance.

IMPERVIOUS - See "Impermeable".

INDUSTRIAL WASTE - See Hazardous Waste Glossary.

LEACHATE - Liquid that has percolated through or drained from hazardous waste or other man-emplaced materials and contains soluble, partially soluble, or miscible components removed from such waste (Federal Reg., 1978).

LINER -A layer of emplaced materials beneath a surface, impoundment, or landfill which serves to restrict the escape of waste or its constituents from the impoundment or landfill (Federal Reg., 1978). In this Manual a liner includes: reworked or compacted soil and clay, asphaltic and concrete materials, spray-on membranes, polymeric membranes, chemisorptive substances, or any substance that serves the above stated purpose.

LYSIMETER - A device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis (EPA, 1972).

MONITORING WELL - See Hazardous Waste Glossary.

MUNICIPAL SOLID WASTE - Solid waste collected from residential and commercial sources in bins and other large containers. Typical components are: plant matter, 8%; paper products, 56%; food wastes, 9%; metals, 8%; ceramics and glass, 8%; plastic , leather, and rubber, 4%; wood, rags, etc.; 7%.(Baum and Parker, 1974).

PESTICIDE - A broad term that includes all chemical agents used to kill animal and vegetable life which interferes with agricultural productivity regardless of their mode of action (Hampel and Hawley, 1976).

pH - See Chemistry Glossary.

POLLUTANT - (1) A substance, material, chemical, etc., that renders the carrier medium, i.e., a solid, liquid, or gas, unfit for industrial or domestic use, or presents a potential public health hazard. (2) In this Manual, a pollutant is a substance or material that degrades the quality of, or, directly or indirectly, presents a hazard to all or any of the following sectors of the environment: water, groundwater, air, soil, plants, wildlife, or people.

RUN-OFF - See Hydrology Glossary.

SANITARY LANDFILL (LAND FILLING) - A site where solid waste is disposed of on land in a manner that protects the environment by spreading the waste in thin layers, compacting it to the smallest practical volume, and then covering it with soil by the end of the working day (EPA, 1972).

SANITARY LANDFILLING METHODS - Area, Quarry, Ramp, Trench, and Wet Areas,

Area: A method in which the wastes are spread and compacted on the surface of the ground and cover material is spread and compacted over them.

Quarry: Wastes are spread and compacted in a depression; cover material is generally obtained elsewhere.

Ramp: Cover material is obtained by excavating in front of the working area. A variation of this method is known as the progressive slope sanitary landfilling method.

Trench: Waste is spread and compacted in a trench; the excavated soil is spread and compacted over the waste to form the basic cell structure.

Wet Area: Used in a swampy area where precautions are taken to avoid water pollution before proceeding with the area method (EPA, 1972).

SOLID WASTE - Any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities; does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges (Public Law, 1976).

SOLID WASTE MANAGEMENT - The purposeful, systematic control of the generation, storage, collection, transportation, separation, processing, recycling, recovery, and disposal of solid waste (EPA, 1972).

SUSPENDED SOLIDS - See Chemistry Glossary.

TOE - Bottom of any slope, specifically applied in this Manual to the bottom of the working face of a landfill.

VECTOR - A carrier, e.g., an insect or a rodent, that is capable of transmitting a pathogen from one organism to another (ASCE, 1976).

VOLATILE ACIDS - See Chemistry Glossary.

VOLATILE MATTER - The matter lost from a dry solid waste sample that is heated until it is red in a closed crucible (EPA, 1972).

VOLATILE SOLIDS - Chemistry Glossary

WATER TABLE - See Hydrology Glossary.

WORKING FACE - That portion of a sanitary landfill where waste is discharged by collection trucks and is compacted prior to placement of cover material (EPA, 1972).

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